FRIB Accelerator: Design and Construction Status

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On Behalf of FRIB Accelerator Team & Collaboration

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Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

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- The FRIB accelerator design is executed by a dedicated team of the FRIB Accelerator Systems Division with close collaboration with the Experimental Systems Division headed by G. Bollen, the Conventional Facility Division headed by B. Bull, the Chief Engineer's team headed by D. Stout, and supported by the project controls, procurements, ES&H of the FRIB Project, by NSCL, and by MSU.
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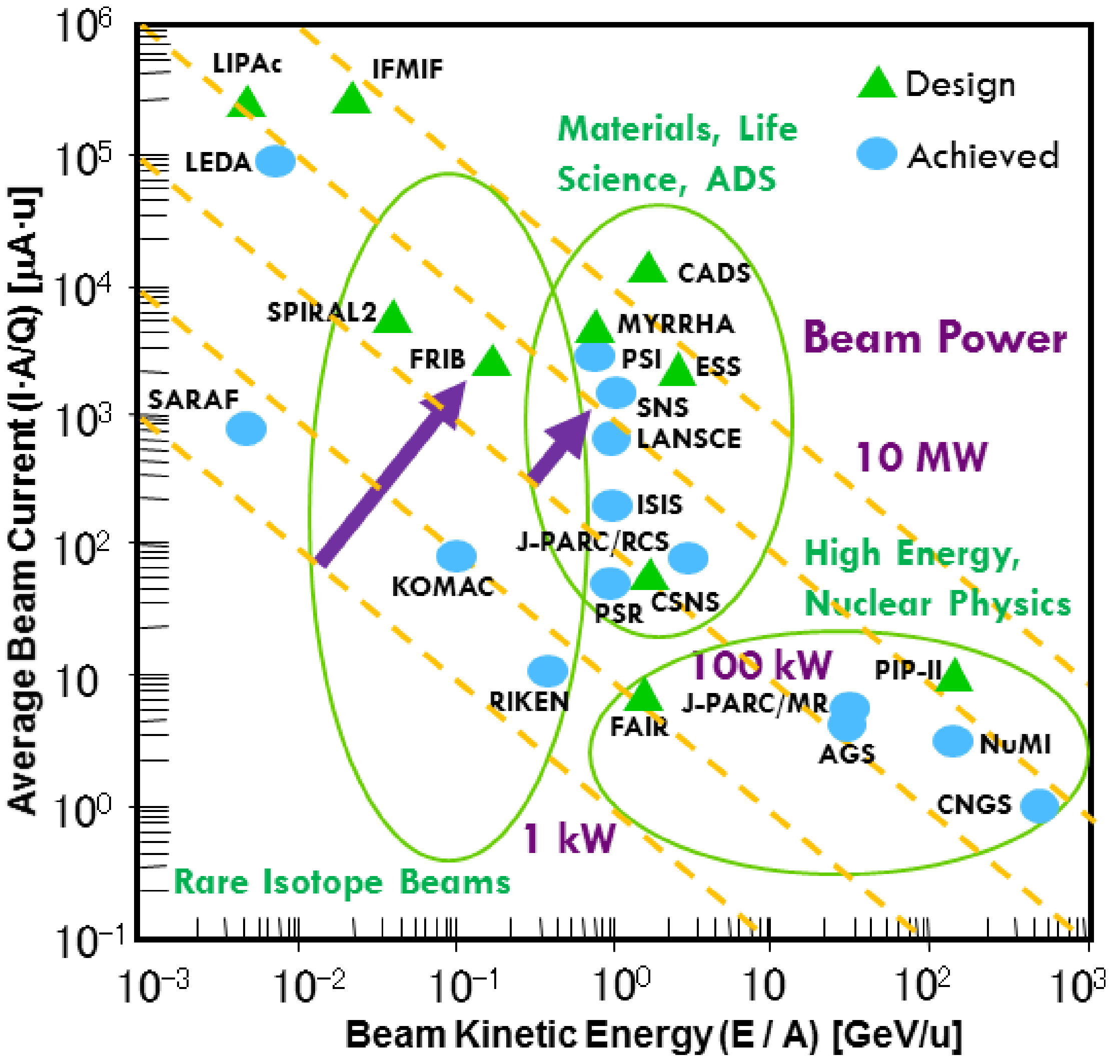
Outline

- Introduction
- Major technology developments
- Design status
- Production infrastructure preparation
- Construction status
- Outlook

▪Introduction

Accelerator Beam-power Frontier

- High energy, nuclear physics (ν, K factories)
  - 1 ~ 400 GeV proton
  - Linac + Synchrotron
- Material, life science, (SNS) accelerator-driven subcritical systems (ADS)
  - 0.5 ~ 3 GeV proton
  - Cyclotron, linac, rapid cycling synchrotron, accumulator
- Rare isotope beams (RIB)
  - 0.01 ~ 1 GeV/u heavy ion
  - Linac, cyclotron, synchrotron
- Material irradiation; isotope
  - ~0.02 GeV/u deuteron; linac



Michigan State University

57,000 people; 93 km^2 area; 552 buildings; US$1.8B annual revenue

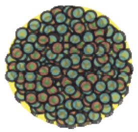
FRIB Project at Michigan State University
Project of $730M ($635.5M DOE, $94.5M MSU)

- 2008-12: DOE selects MSU to establish FRIB
- 2009-6: DOE and MSU sign corresponding cooperative agreement
- 2010-9 CD-1: conceptual design complete & preferred alternatives decided
- 2013-8 CD-2/CD-3a: performance baseline, start of civil construction & long lead procurement
- 2014-8 CD-3b: start of technical construction
- 2022-6 CD-4: construction completion

Growth from more than 500 employees today at NSCL, MSU

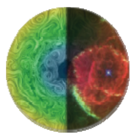
More than 1200 registered user at NSCL user group and at FRIB user organization

The Science of FRIB is Endorsed by NSAC and NRC



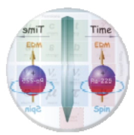
Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Understand the nuclear force in terms of QCD
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



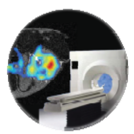
Astrophysical processes

- Chemical history of the universe
- Model explosive environments
- Properties of neutron stars, EOS of asymmetric nuclear matter



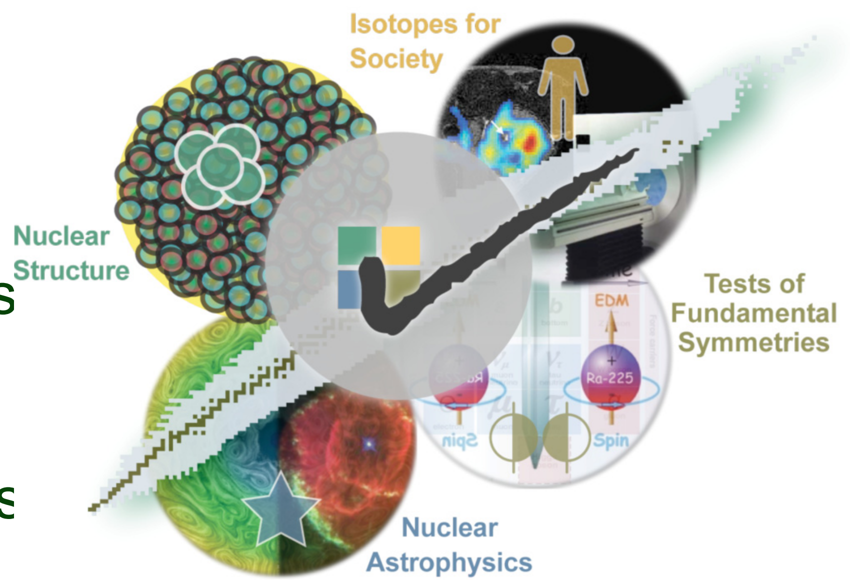
Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei

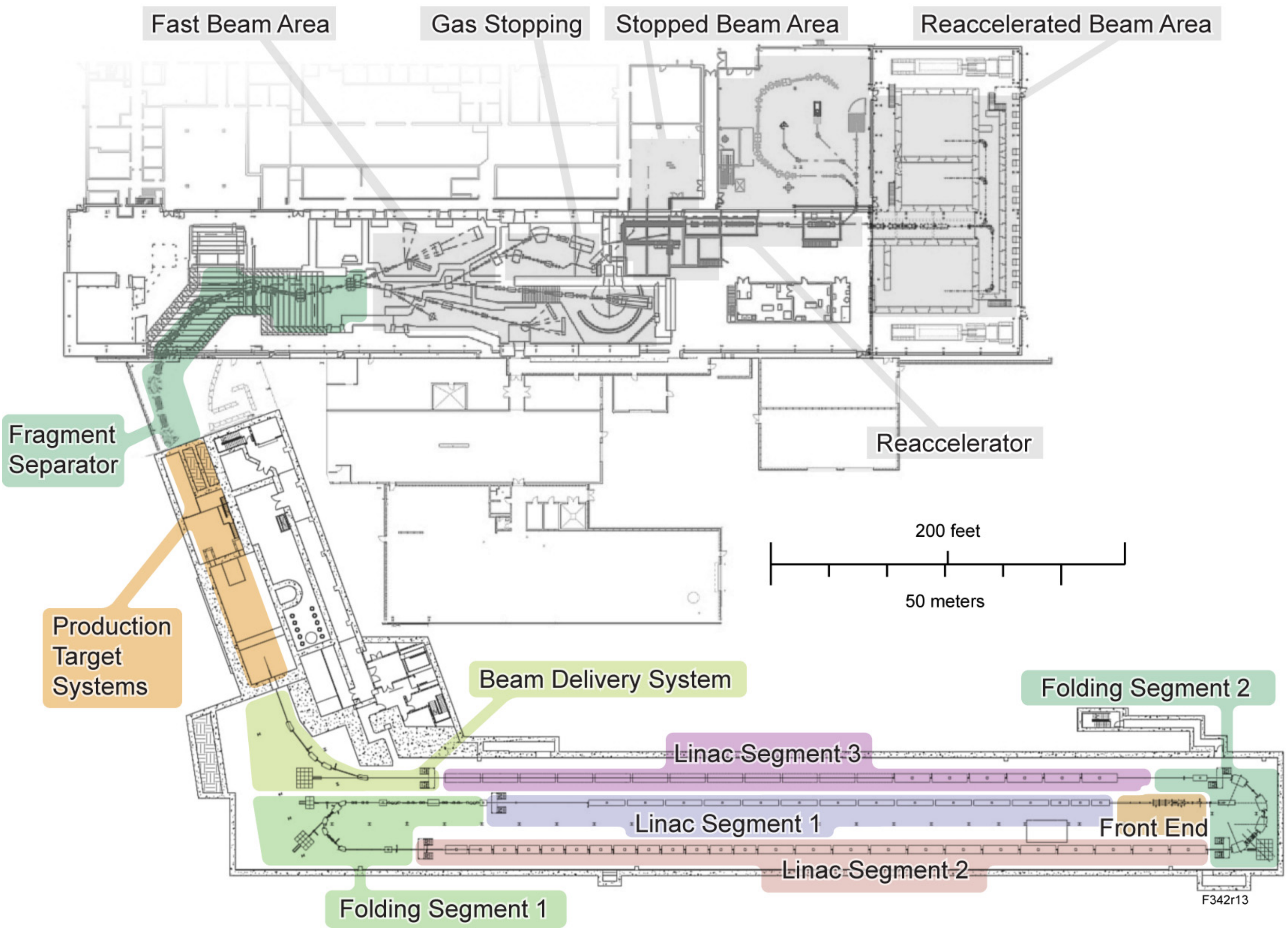


Societal applications and benefits

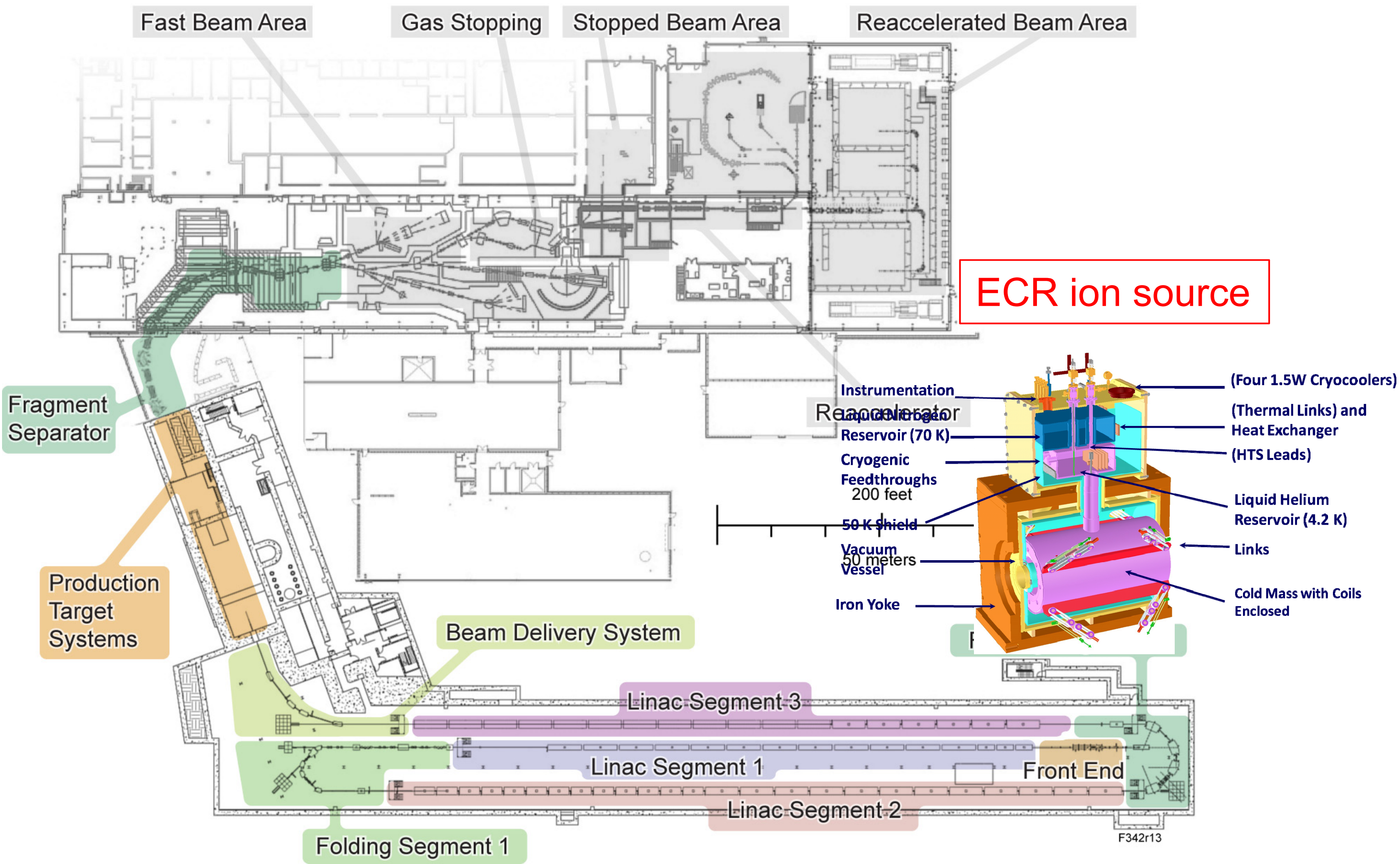
- Bio-medicine, energy, material sciences, national security



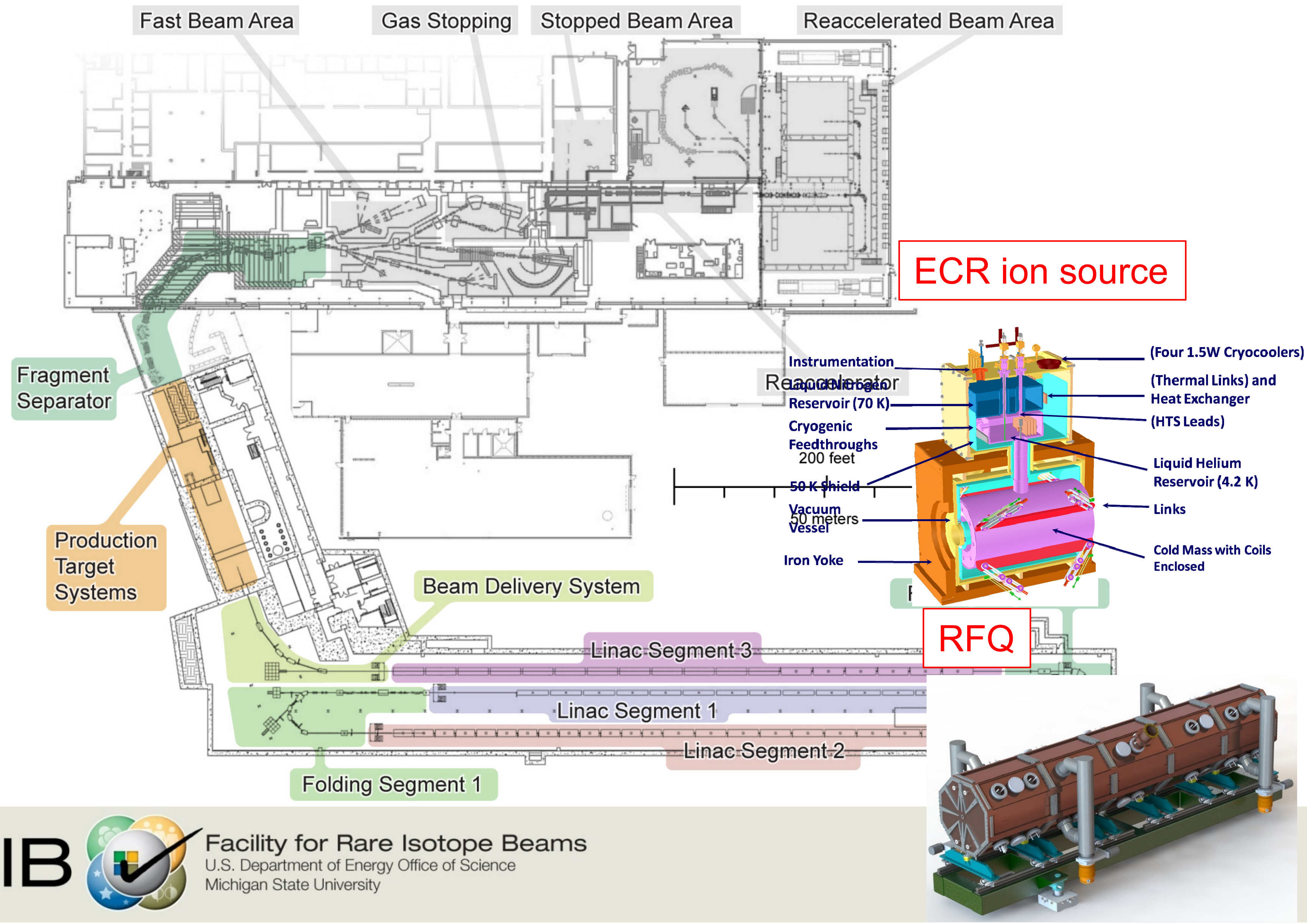
FRIB Accelerator Complex Subsystems



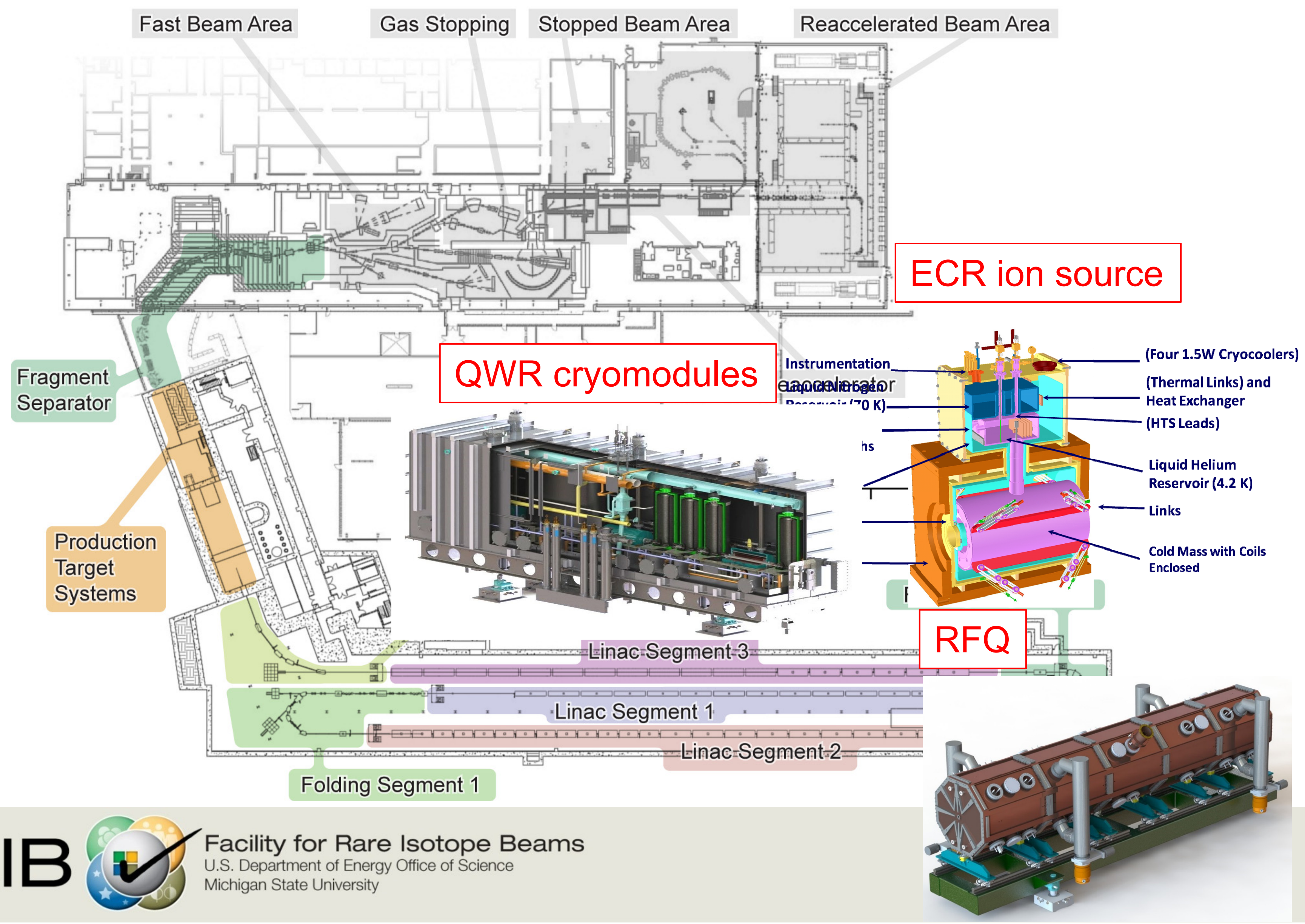
FRIB Accelerator Complex Subsystems



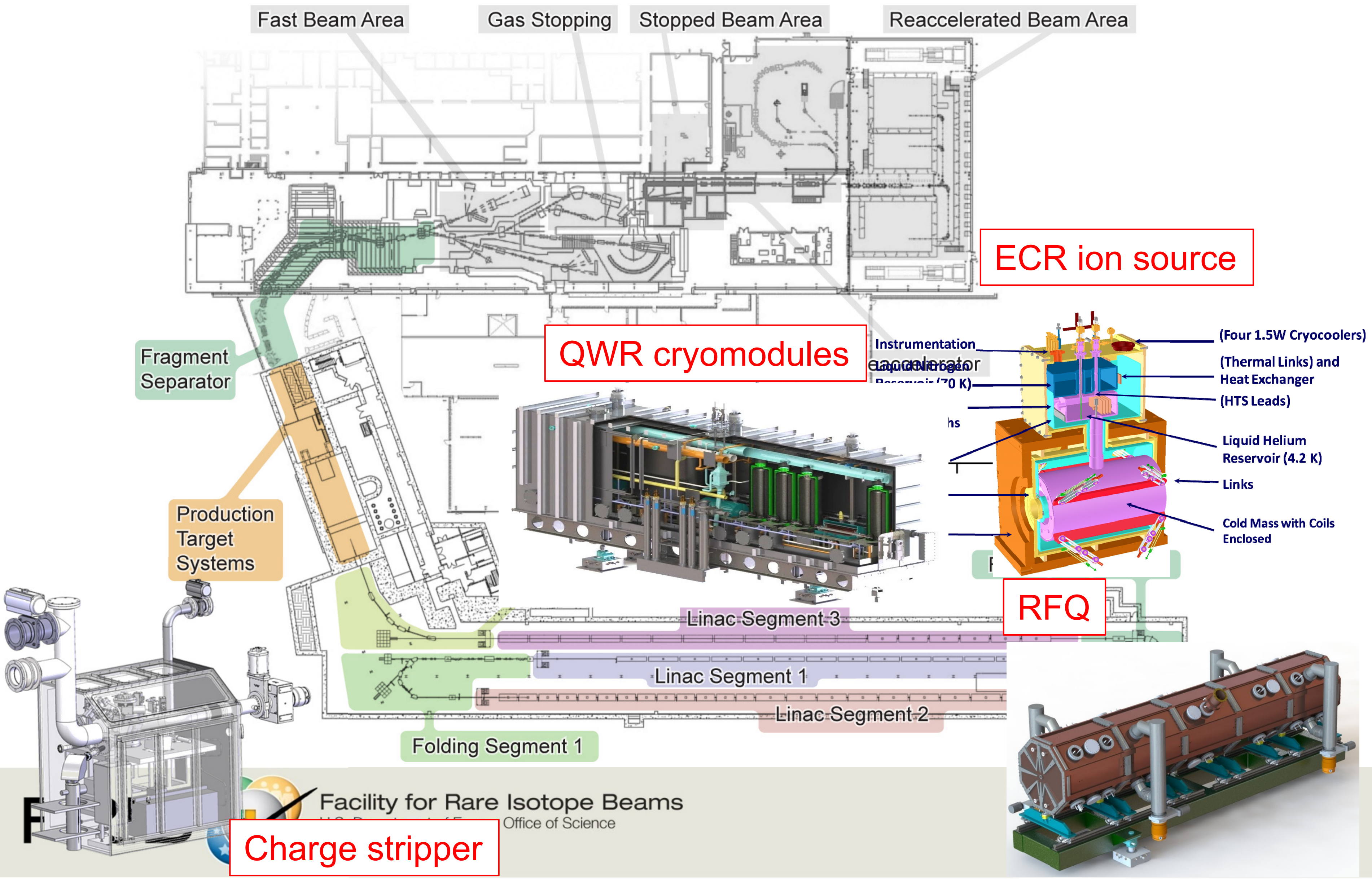
FRIB Accelerator Complex Subsystems



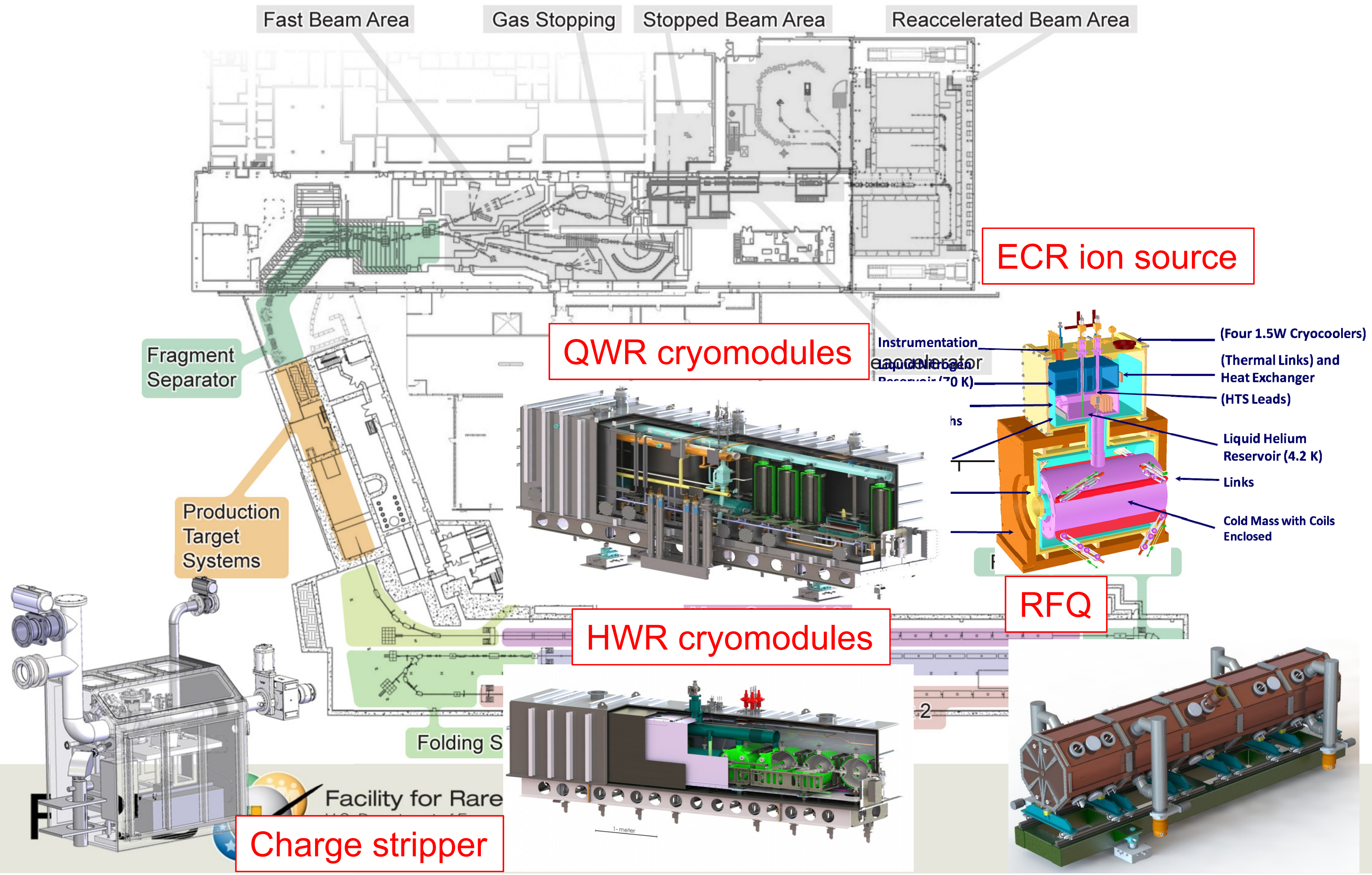
FRIB Accelerator Complex Subsystems



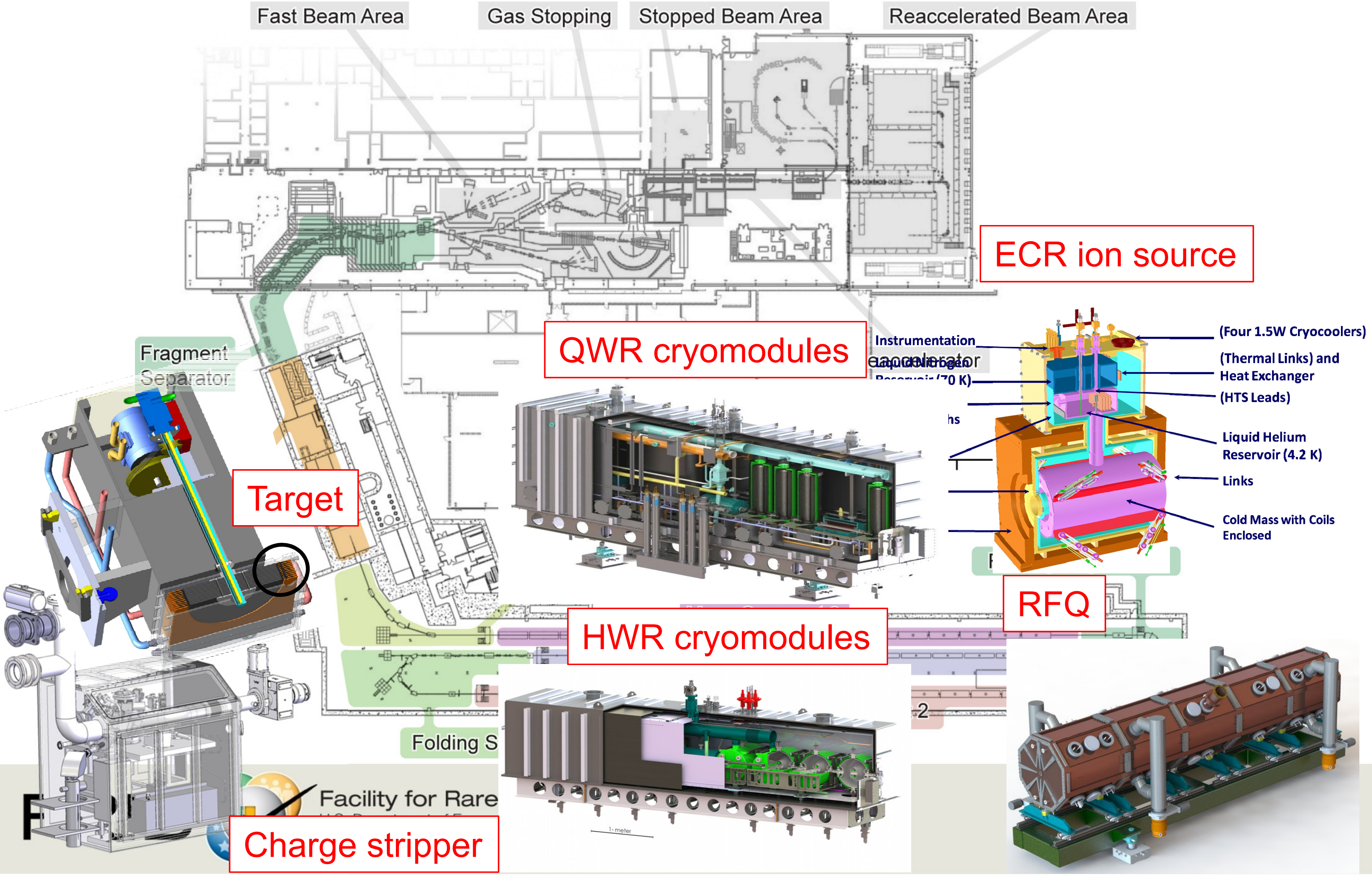
FRIB Accelerator Complex Subsystems



FRIB Accelerator Complex Subsystems



FRIB Accelerator Complex Subsystems



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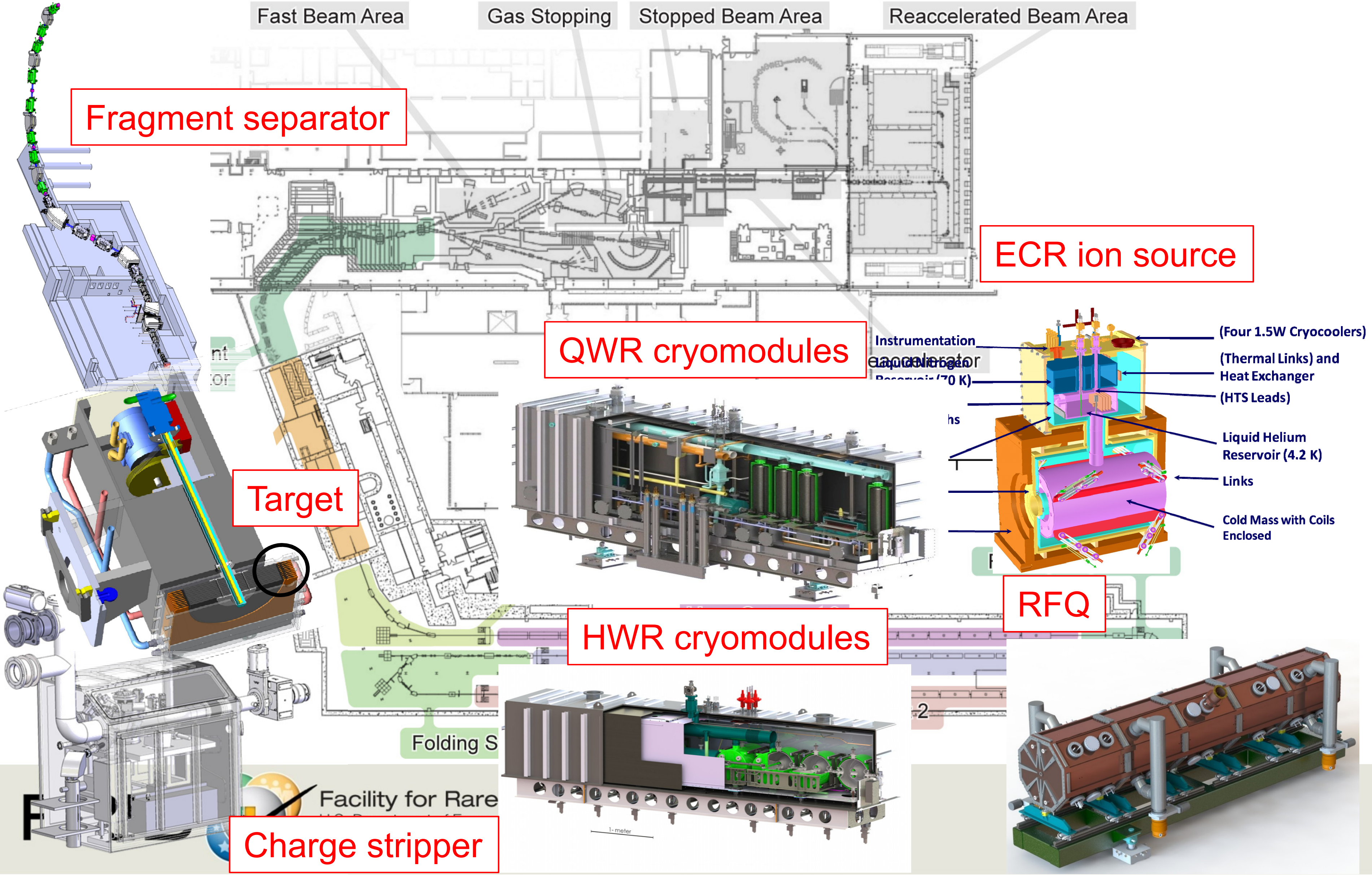

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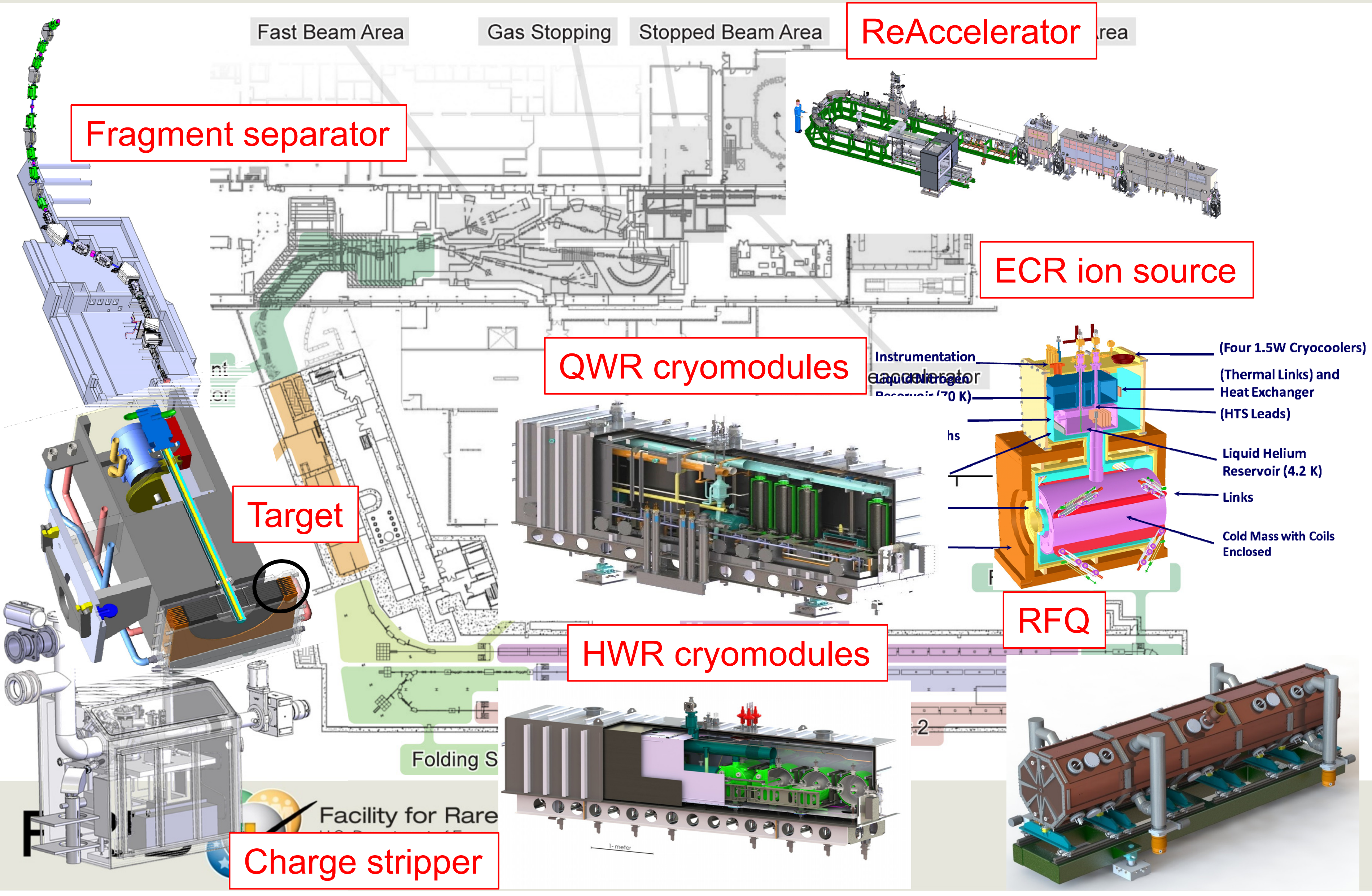
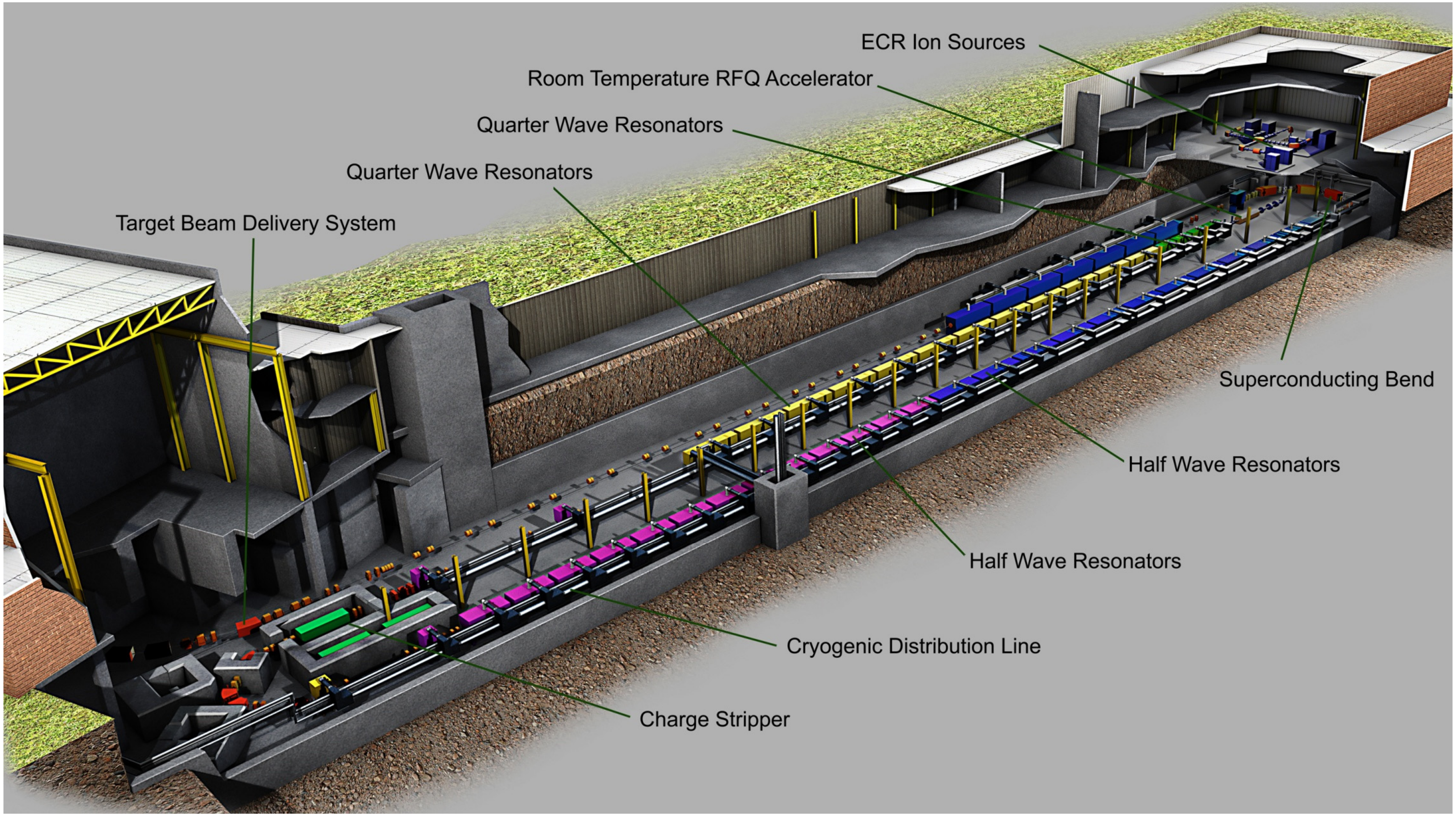


FRIB Driver Linac Layout

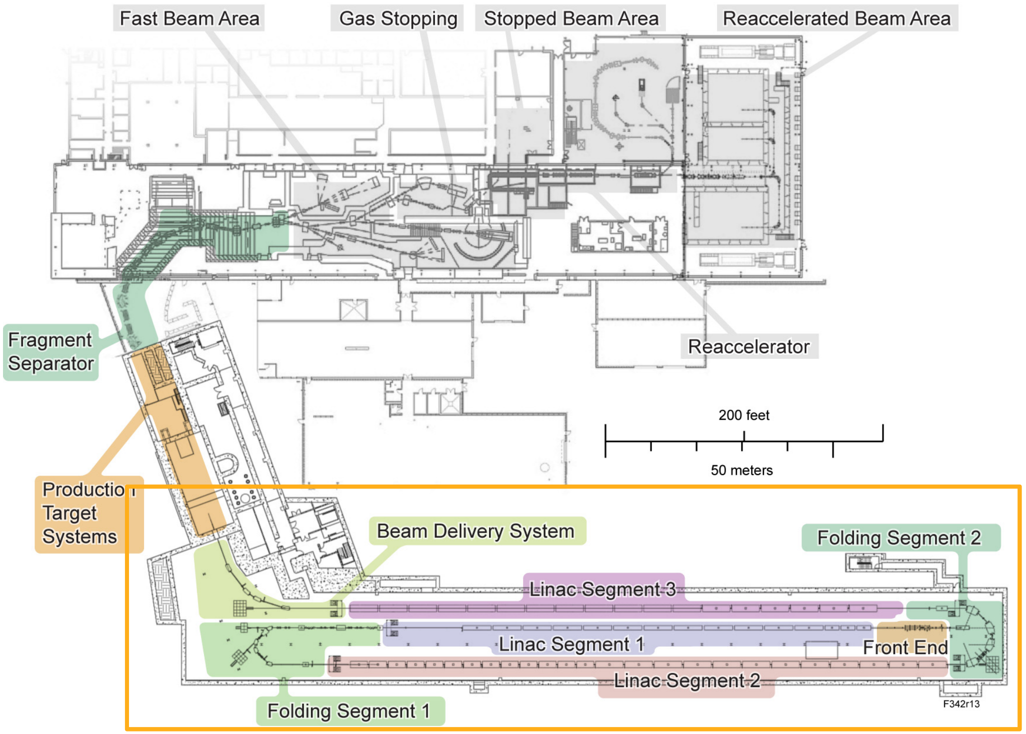


FRIB Civil Construction Site

Accelerator Tunnel Civil Construction Completed

FRIB Civil Construction Site
Accelerator Tunnel Civil Construction Completed

FRIB Accelerator Design Requirements

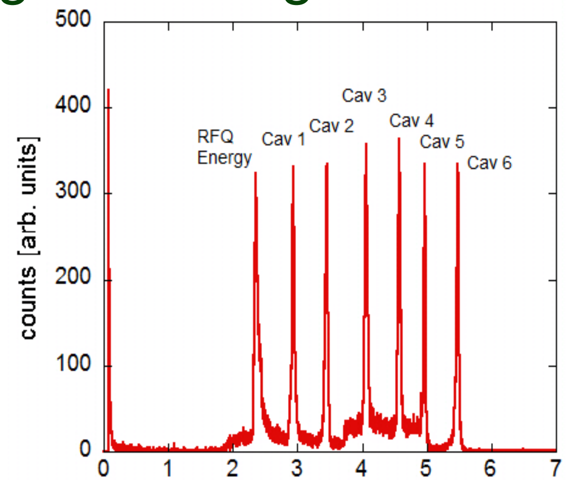


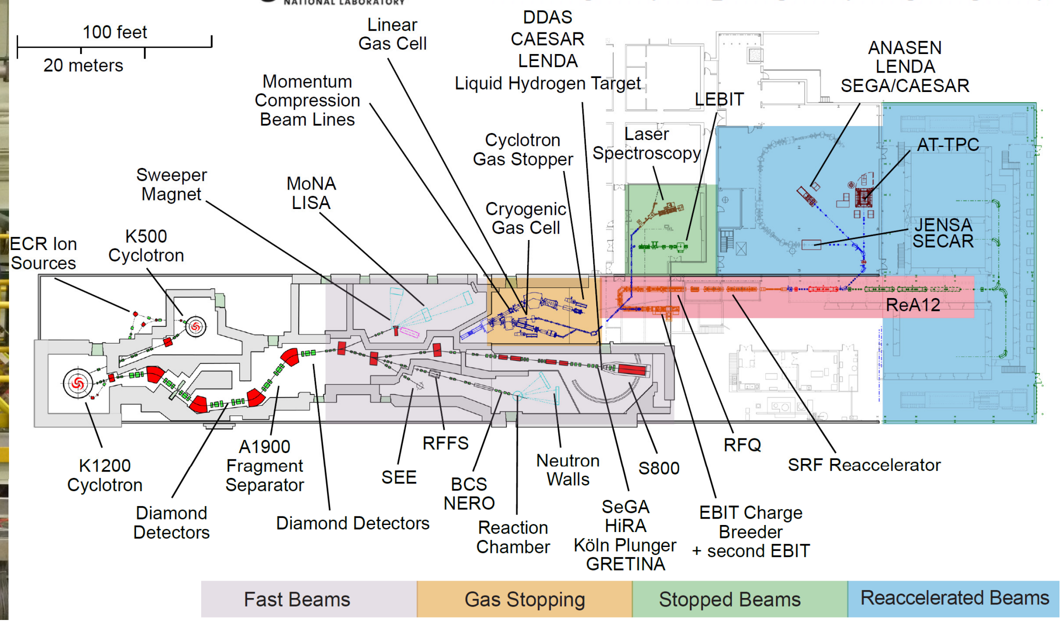
- Delivers FRIB accelerator as part of a DOE-SC national user facility with high reliability & availability
- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400 kW
- Satisfy beam-on-target requirements

- Option for energy upgrade to >400 MeV/u by filling vacant slots with ~ 12 cryomodules
- Maintain Isotope Separation On-Line (ISOL) option
- Upgradable to multi-user simultaneous operation of light / heavy ions with addition of a light-ion injector

Cryomodule Performance Demonstrated: Rare Isotope ^{76}Ga Produced and Accelerated

- Superconducting cyclotrons accelerate ^{76}Ge beam to 130 MeV/u; ^{76}Ga produced; stopped in the ANL gas cell; Charge Breeding in the EBIT Source
- Re-acceleration in the ReA accelerator
  - Using Radio Frequency Quadrupole (RFQ) and β=0.041 cryomodules
- SRF technology mature for FRIB project

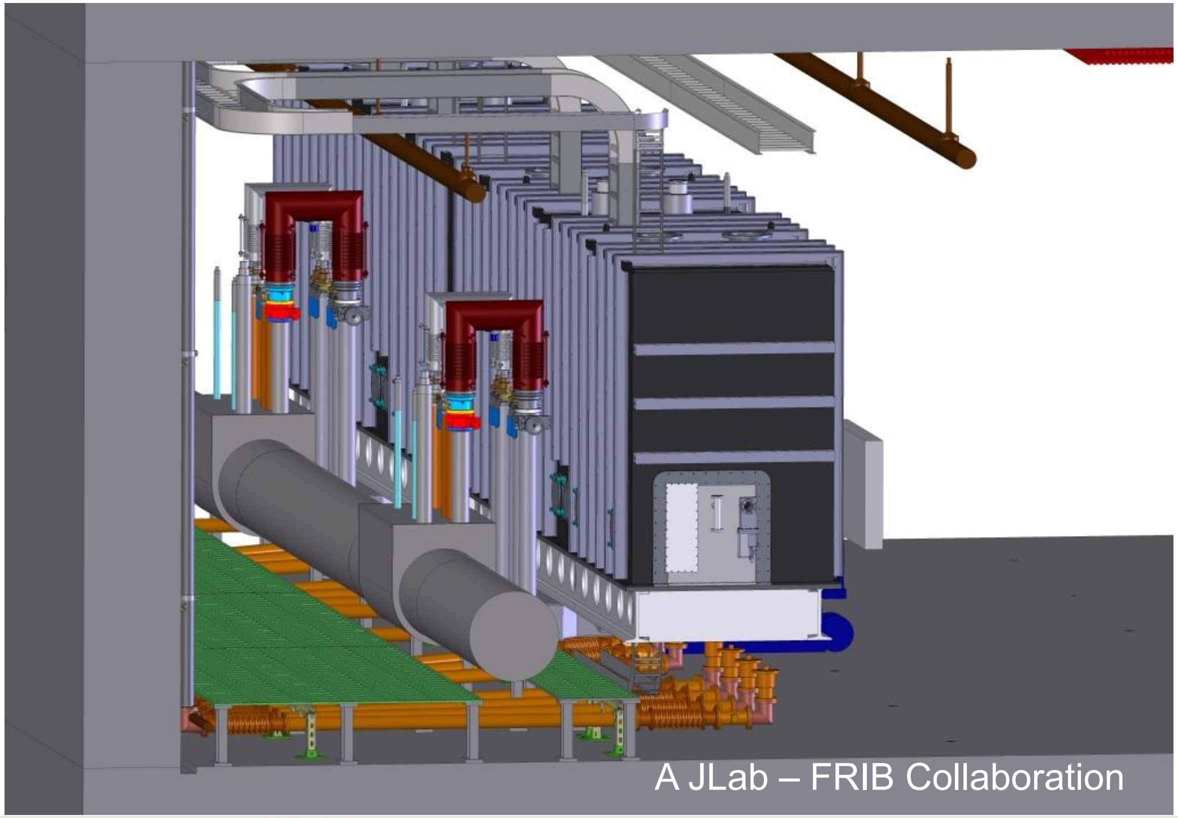




- Major technology developments

Integrated Cryogenics

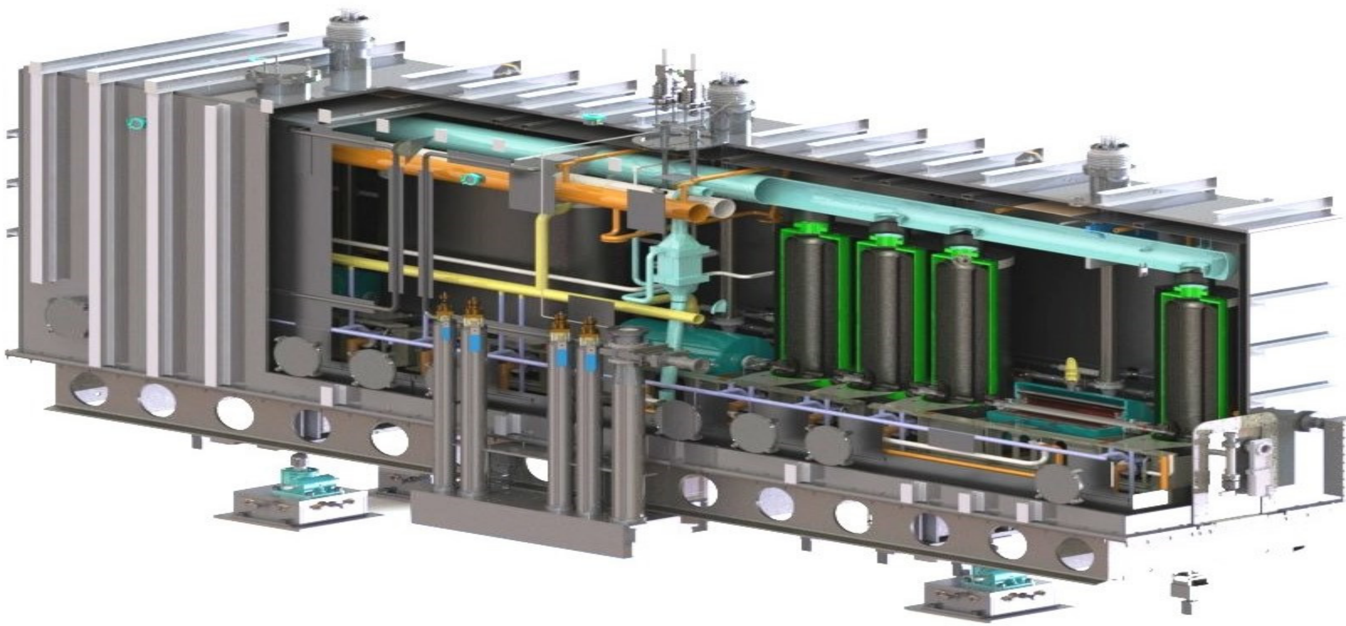
- Cost significant: cryogenics systems accounts for ~ 20% linac cost
- An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems is key to efficient SRF operations.



- Ganni cycle: floating pressure process
- Distribution lines segmented
- Cryomodules connected with U-tubes: maintenance
- 4-2 K heat exchangers housed inside cryomodules

Bottom Up Cryomodule

- Facilitate assembly efficiency; simplify alignment; and allow U-tube cryogenic connections for maintainability
- Resonators and solenoids supported from the bottom
- Cryogenic headers are suspended from the top for vibration isolation



- All resonators operate at 2 K
- All solenoids operate at 4.5 K
- Local magnetic shielding for 1.5 μT remnant field

Prototype Cryomodule & Cryodistribution Tested

Bottom-up Design Validated and Mature for FRIB Production

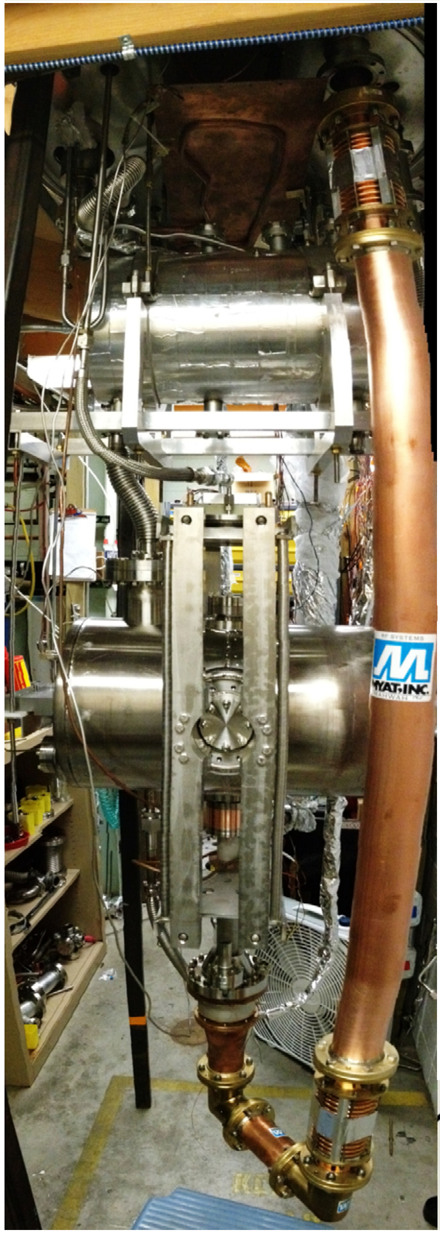
First FRIB prototype cryomodule (β=0.085)
Assembled and successfully tested at MSU

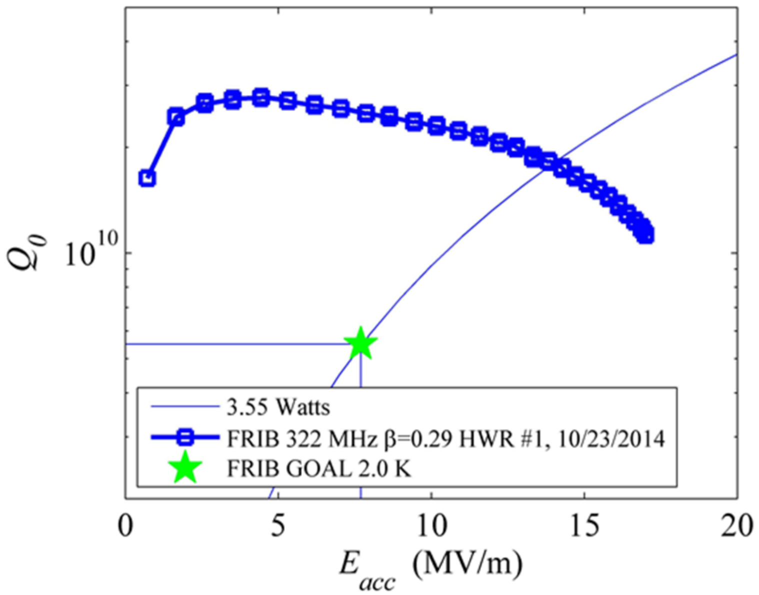
Objective Measures	Date
Quarter Wave Resonator (QWR) certified	Done, 06/2014
Integrated QWR test with ANL coupler	Done, 06/2014
Coldmass assembled on baseplate	Done, 10/2014
Alignment survey complete	Done, 11/2014
Cryomodule assembly complete and test start	Done, 03/2015
Alignment verification	Done, 04/2015
Cavity 24-hour lock and vibration control verification	Done, 05/2015
Cryomodule test completion	5/2015

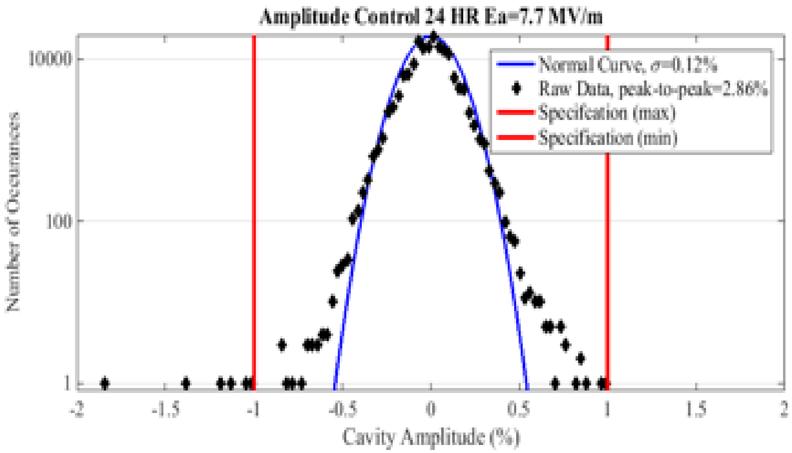
- Prototype test started on-time; designs validated
- Fed lessons learned into FRIB production design
- Major procurements launched on β=0.085 production

	Gradient	Detuning		Phase		Amplitude	
4.3K test	E_a (MV/m)	σ (Hz)	pk-pk (Hz)	σ (deg)	pk-pk (deg)	σ (%)	pk-pk (%)
Measured QWR 1	5.7	0.5	9.7	0.08	0.68	0.11	1.23
Measured QWR 2	5.7	0.6	16.7	0.08	0.76	0.16	1.58
FRIB goal 2K	5.7	<2.25	<20	<0.25	<2	<0.25	<2

Low-β Superconducting RF







- Superconducting RF starting from 0.5 MeV/u
- Optimum performance at low production cost:
  - cavity geometries
  - material
  - mechanical solutions,
- Designs validated:
  - Vertical Dewar tests
  - Integrated tests of the cavity, power coupler, tuner, and ancillary systems
  - Assembled cryomodule testing in the bunker

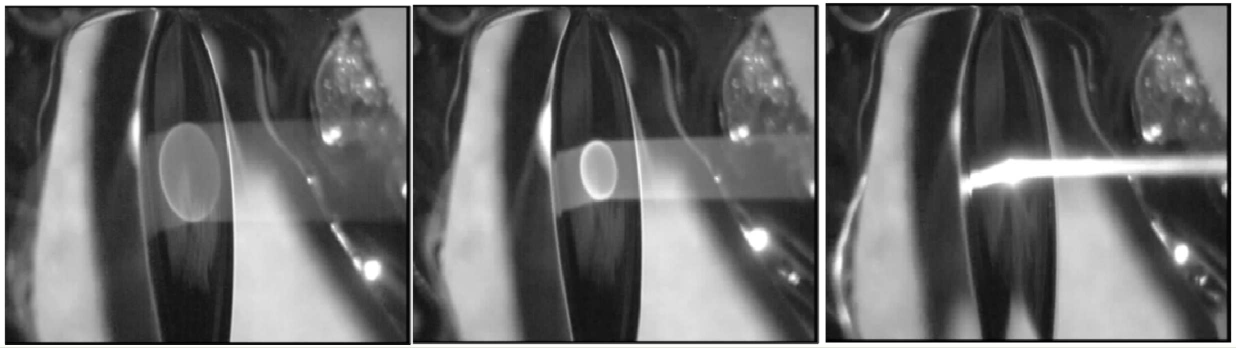
Liquid Lithium Charge Stripper

Successful LANL IS Restoration at MSU & Beam Power Test at ANL

- Liquid lithium film established with controllable thickness and uniformity
- LEDA Ion Source (IS) beam commissioned at MSU
  - Beam commissioned at MSU after restoring with new cooling and power supply system after more than 10 years of storage.
- Beam power tests on liquid lithium film successfully performed at ANL
  - The film sustained ~200% of FRIB maximum power density deposition

LANL LEDA ion source restored at MSU

Liquid lithium film flowing at high speed (~ 50 m/s) intercepting a proton beam of about 60 kV at ANL. The test produced power deposition densities similar to the FRIB uranium beams.

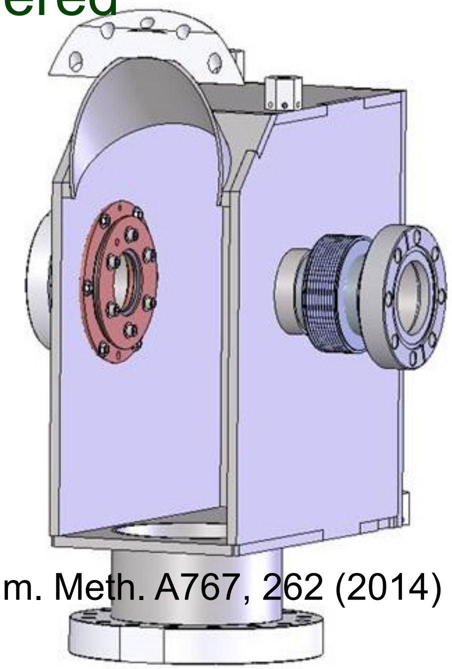


Loss Detection and Machine Protection
Multi-time Scale Mitigation Necessary

- Low-energy ions has low detection sensitivity & high impact
- Must mitigate both acute & chronicle beam loss (by beam inhibition)

Mode	Time	Detection	Mitigation
FPS	~35 μs	LLRF controller Dipole current monitor Differential BCM Ion chamber monitor Halo monitor ring Fast neutron detector Differential BPM	LEBT bend electro-static deflector
RPS (1)	~100 ms	Vacuum status Cryomodule status Non-dipole PS Quench signal	As above; ECR source HV
RPS (2)	>1 s	Thermo-sensor Cryo. heater power	As above

- Halo monitor rings in development
- Differential BCM used
- Thermo-sensors considered



Z. Liu et al, Nucl. Instrum. Meth. A767, 262 (2014)

- Design status

Engineering Design Stages & Requirements

- Preliminary design
  - Corresponds to the project baselining (CD-2 in 2013)
  - Three years after the completion of the conceptual design (CD-1 in 2010)
- Intermediate design
  - System requirements, specifications and interfaces finalized
  - Safety hazards identified and mitigated
- Final design
  - Models and/or drawings produced ready for procurement
  - Statement of work (SOW) and Acceptance criteria listing (ACL) developed
  - Procurement strategy defined
  - Installation and commissioning plans developed
- Presently, overall accelerator systems design is ~ 80% complete as measured by the Final Design Plan

Criteria on Design Maturity

- Are requirements and interfaces defined?
- Is appropriate prototyping completed?
- Do prototypes meet specifications?
- Is the detailed design completed?
- Has the design been reviewed?
- Does a procurement/fabrication plan exist?

Designs Continue to be Reviewed
All Comments and Recommendations Tracked and Addressed

- Project Reviews
  - Accelerator Systems Advisory Committee (Ozaki) – 2/11; 11/11; 6/12; 12/12; 6/13; 12/13; 4/14; 12/14
  - MSU Independent Reviews – 4/12 (Holtkamp); 4/14 (Harrison)
  - Lehman/Meador Review – 3/11; 9/11; 4/12; 10/12; 6/13; 6/14; 3/15
- Accelerator Systems external peer reviews and workshops since CD-1
  - 10/2010: Accelerator Alignment External Review
  - 01/2011: Cryomodule Heat Source External Review
  - 02/2011: Machine Protection, Diagnostics Timing
  - 04/2011: Accelerator Lattice External Review
  - 05/2011: Diagnostics External Review
  - 05/2011: Electrical Grounding Workshop
  - 07/2011: Controls External Review
  - 08/2011: Cryogenic External Review
  - 08/2011: SRF External Review
  - 08/2011: Cryomodule (0.53) External Review
  - 08/2011: Front End External Review
  - 10/2011: Magnets External Review
  - 10/2011: Charge Stripper External Review
  - 11/2011: Installation, Pre-ops, Commissioning
  - 12/2011: RF & Power Supply External Review
  - 01/2012: Diagnostics Preliminary Design Peer Review
  - 01/2012: Personnel Protection System Workshop
  - 01/2012: Vacuum, Beam Dump, Collimator Review
  - 02/2012: Lithium Stripper Safety Review
  - 07/2012 SRF Subsystem Review
  - 09/2012: Utility Interface External Review
  - 09/2012 Final Engineering Design Approach Review
  - 11/2012: HP Source Magnet/Coldmass Workshop
  - 11/2012: FRIB Vacuum Workshop
  - 02/2013: ReA coupler, SRF fabrication, TDCM, ETCM
  - 03/2013: Magnet Shielding Workshop
  - 07/2013: RF and Power Supplies Intermediate
  - 07/2013: Personnel Protection System Intermediate
  - 08/2013: Artemis Ion Source / HV Platform Inter. Design
  - 09/2013: ReA6 Cryomodule Project Status Review
  - 10/2013: QWR Prototype Cryomodule Final Design
  - 10/2013: Lithium Charge Stripper Intermediate Design
  - 10/2013: MPS and GTS Intermediate Design Review
  - 10/2013: Alignment Intermediate Design Review
  - 11/2013: Cryodistribution Intermediate Design Review
  - 11/2013: HWR Cryomodule Intermediate Design
  - 11/2013: ASD Room-temperature Dipole Magnet Interm.
  - 11/2013: ASD Superconducting Magnet Final Design
  - 11/2013: ASD RT Optical Element Intermediate Design
  - 11/2013: Diagnostics Intermediate Design Review
  - 11/2013: MEBT Bunch Preproduction Review
  - 11/2013: Low-level Controls Intermediate Design
  - 01/2014: FRIB In-depth Technical Interface Series
  - 03/2014: Cryomodule Maintenance Workshop
  - 03/2014: Machine Protection Systems Workshop
  - 03/2014: ESH Advisory Committee Review
  - 03/2014: Prelim. Start-up & Commissioning Plan Review
  - 04/2014: Artemis Ion Source / HV Platform Final Design
  - 05/2014: ASD RT Magnet Final Design Review
  - 06/2014: 0.53 HWR Cryomodule Final Design Review
  - 06/2014: Cryomodule SC solenoid Final Design review
  - 08/2014: RF and Power Supply Final Design Review
  - 08/2014: Lithium Stripper Final Design Review
  - 09/2014: ECR Cold Mass Design Review
  - 09/2014: Alignment Network Final Design Review
  - 09/2014: Vacuum In-progress Design Review
  - 09/2014: Cryoplant and Cryodistribution Final Design Review
  - 11/2014: ICFA Workshop on High Power Hadron beams
  - 02/2015: ASD Diagnostics Final Design Review
  - 02/2015: ESHAC Review
  - 05/2015: EVMS Review
  - 05/2015: Vacuum Final Design Review
  - 05/2015: Personnel Protection System In-progress Review
  - 05/2015: Front End Controls Final Design Review

- Production infrastructure preparation

“SRF High Bay” Constructed at MSU

Objective Measures	Date
Ready-for-equip.	01/2014
Beneficial occu.	05/2014
Clean 1st cavity	07/2014
Coord. measure.	09/2014
Degassing furnace	10/2014
Etch 1st Cavity	12/2014
Cryogenics system	09/2015
RF test 1st cavity	11/2015
Vertical test area	01/2016
Cryomodule test	09/2016

- Production throughput:
  - 5 cavity per week
  - 1 cryomodule per month

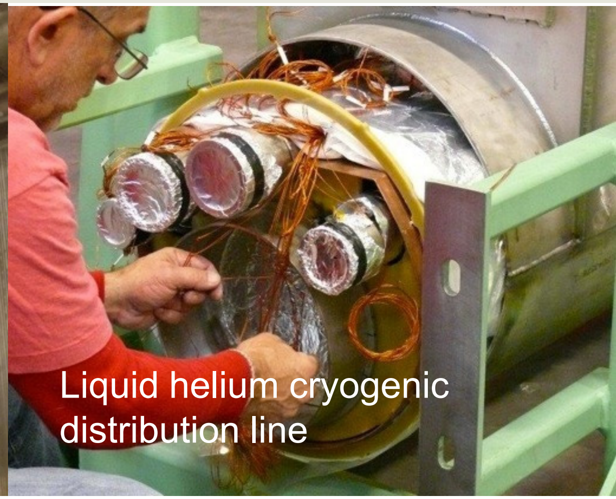
- Construction status

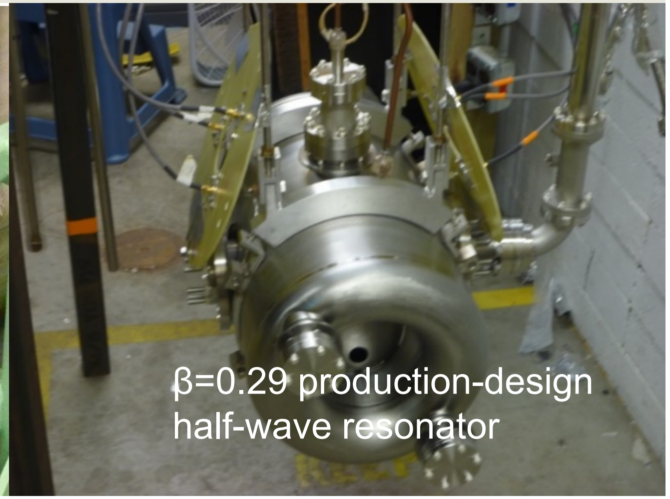
FRIB Accelerator Construction Status

- Technical construction officially started in 2014 (CD-3b)
  - 35% for in-house labor: critical processing and assembly; one-of-a-kind
  - 65% for material, work-for-others efforts at partner laboratories, and procurements from industries
- Major accelerator **long-lead procurements** prepared prior to CD-2/3a
  - 4.5 K cryogenic refrigeration "cold box"
  - Cryogenic distribution
  - Niobium material for SRF cavities
  - Pre-production of the SRF cavities
  - Radio frequency quadrupole linac (RFQ)
  - Electron Cyclotron Resonance ion source (ECR).
- Presently, 65% of major procurements (>US$50k) are spent or committed

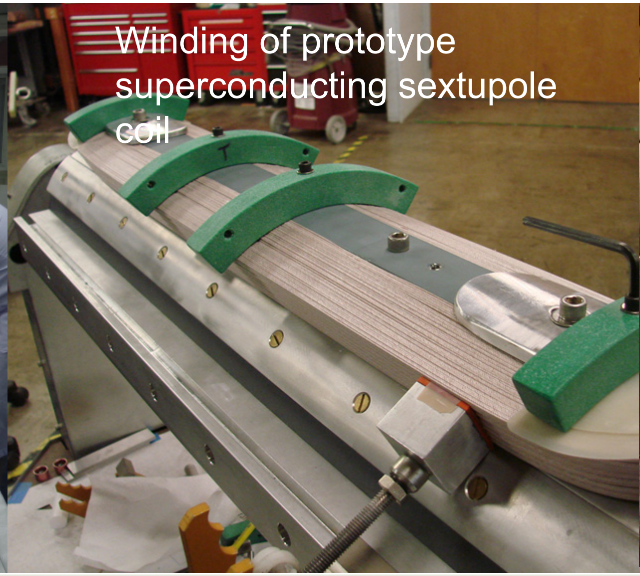
Long-lead Procurements Well Progressing


4.5 K helium refrigeration system


Liquid helium cryogenic distribution line


β=0.29 production-design half-wave resonator


Inspection of niobium material

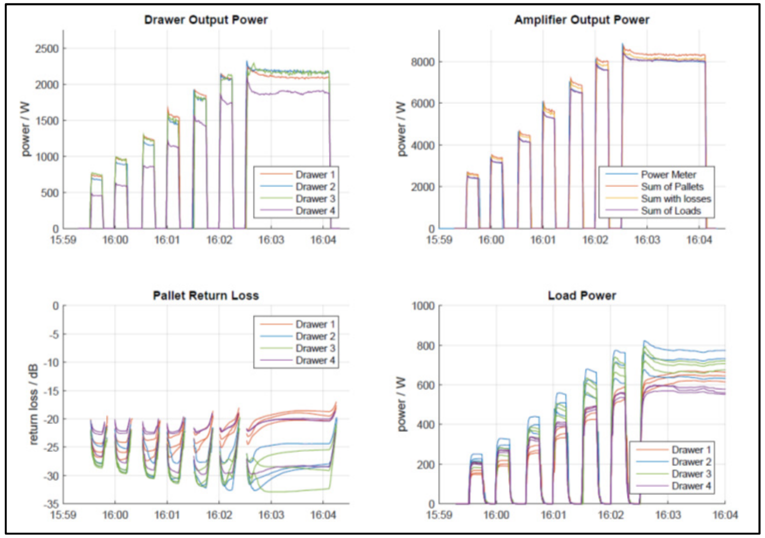

Winding of prototype superconducting sextupole coil


RFQ segment 1 after brazing

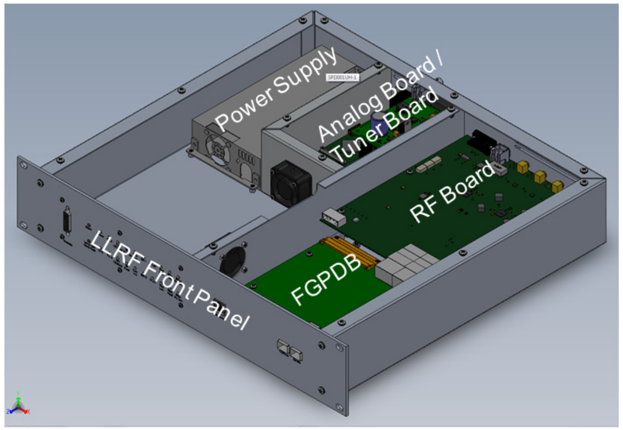
RF System: Solid-State Amplifier Procured; Rigid Transmission Lines Installed

8 kW 322 MHz amplifier for β=0.53 HWRs

Amplifier tested with 100% reflection > 8 kW

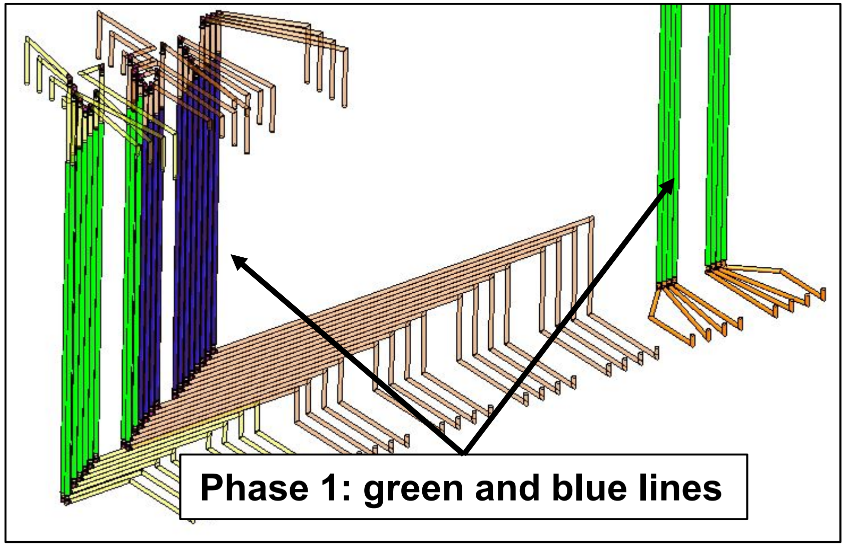


Analog interface board for LLRF control



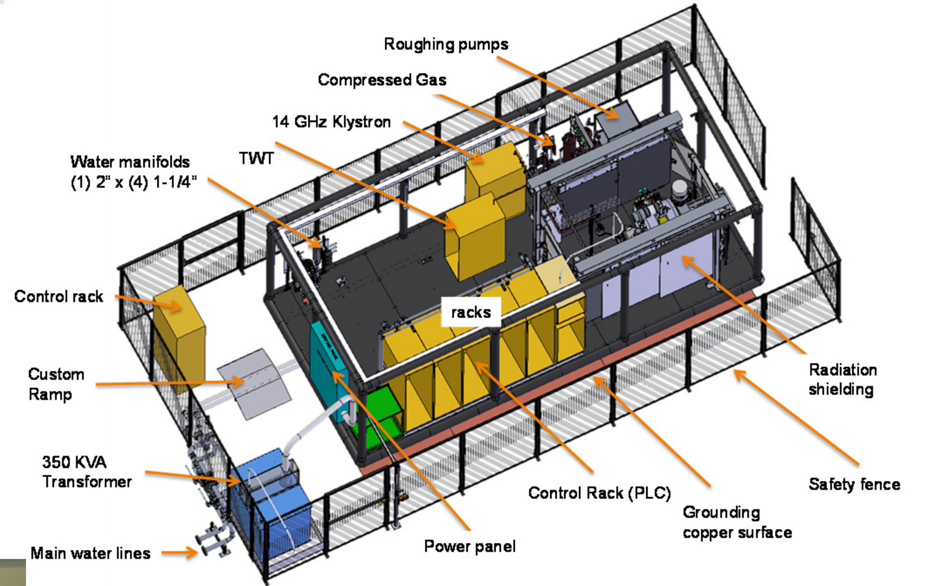
Conduits for the rigid transmission lines

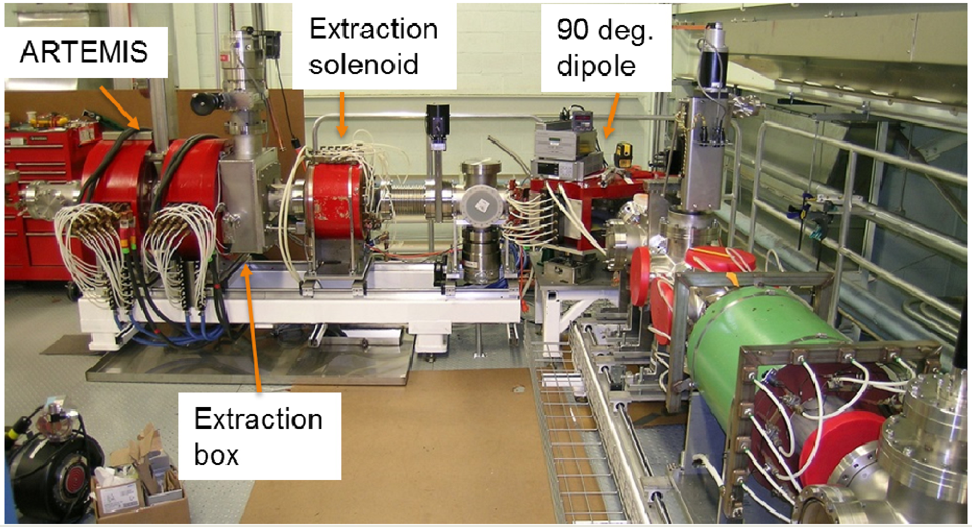
RF transmission line layout



FRIB RT Ion Source Near Completion
High Voltage Platform Construction Started

- Aiming at installation of the Room Temperature (RT) source as soon as the building is Ready-for-Equipment
- High-voltage and radiation hazard mitigation process pursued
- Parallel efforts in developing the high-power superconducting ion source

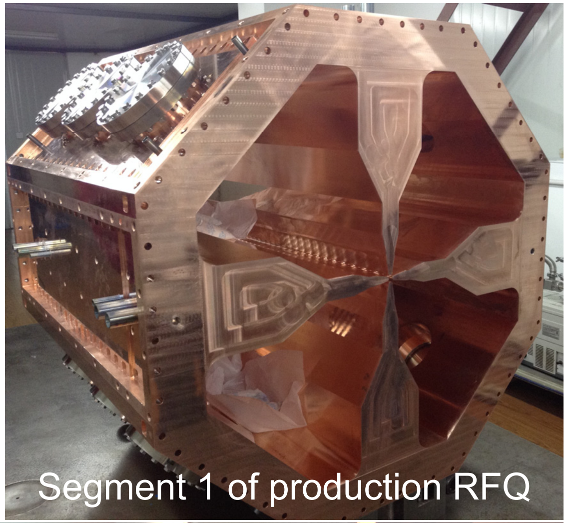




RFQ Segment 1 & 2 Successfully Built
Quality Control of Remote Industrial Vendor Demonstrated

- Independently contracting with qualified third-party "local" institute to provide quality control and coordination
- Weekly or bi-weekly three-party teleconferences followed by action items
- Frequent FRIB staff visits & risk mitigation
- Complete transparency and prompt issue mitigation
- Planning early RFQ commissioning in tunnel
  - Project schedule allows up to a year of high power test in the tunnel upon accelerated tunnel RFE

Objective Measures	Date
Contract awarded; three party engaged	Done, 03/2013
Full cross section prototype tested	Done, 02/2014
Segment 1 (total 5) completed	Done, 11/2014
Fabrication, low-power tuning complete	01/2016
Installation followed by test in FRIB tunnel	03/2016

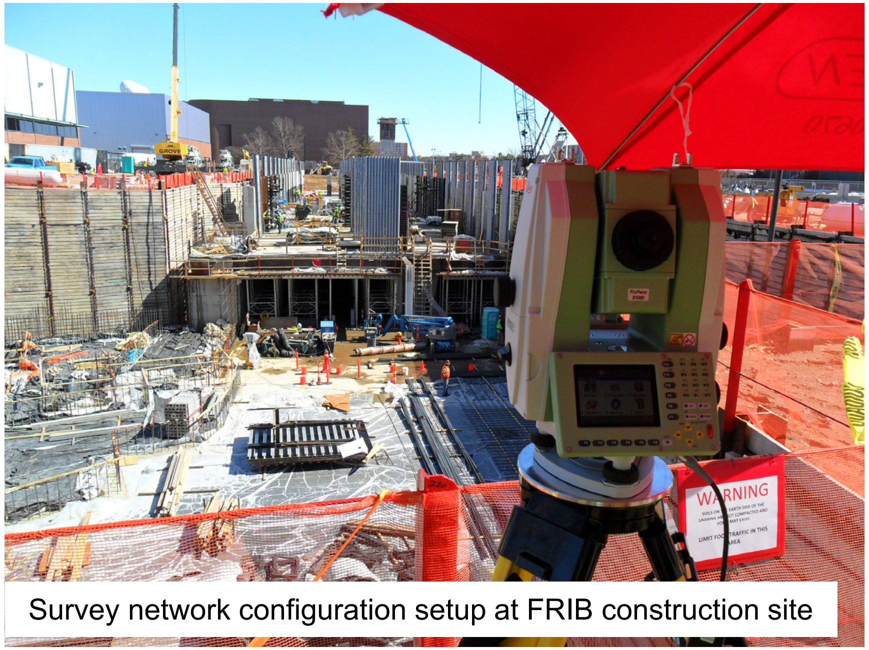

Segment 1 of production RFQ


FRIB staff inspecting the RFQ at vendor site

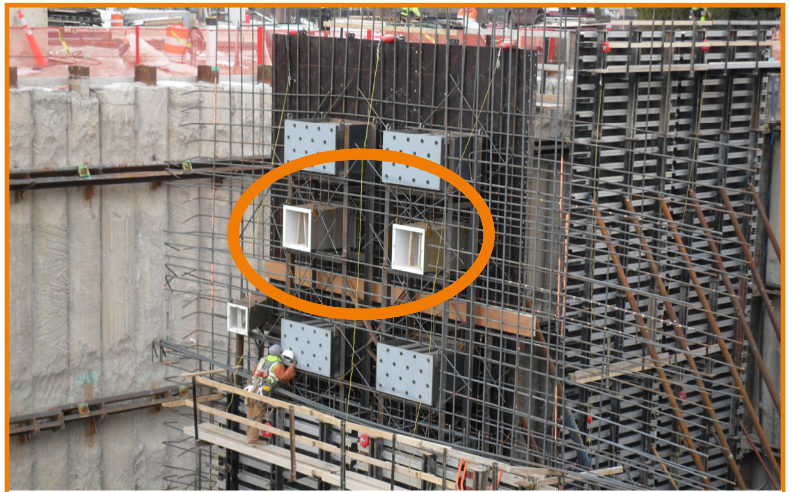
Alignment Network Monuments Installed
Monument Installation at both NSCL & FRIB Sites

- Closely coordinating with conventional facility construction
- Alignment network integrating FRIB new construction with existing NSCL site
- Monitoring construction ground settlement and abnormalities
- Preparing for early equipment installation and tunnel occupancy

Monuments grouted for permanence



Survey network configuration setup at FRIB construction site



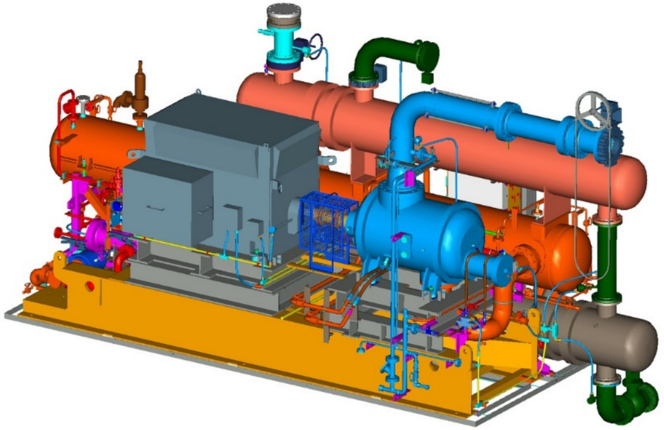
Construction verification measurements, target cell north wall alignment portal imbeds, 28 January 2015

Cryogenic Major Work Scope On Track
4 K Cold Box; Warm Compressors; Tunnel Transfer Lines

- 4 K Cold Box
  - Final design reviewed; fabrication underway; ready for installation spring 2016

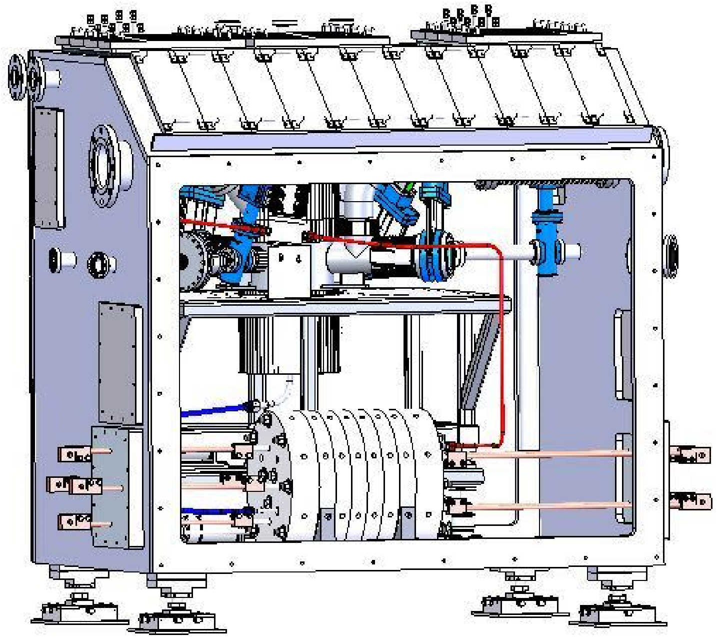


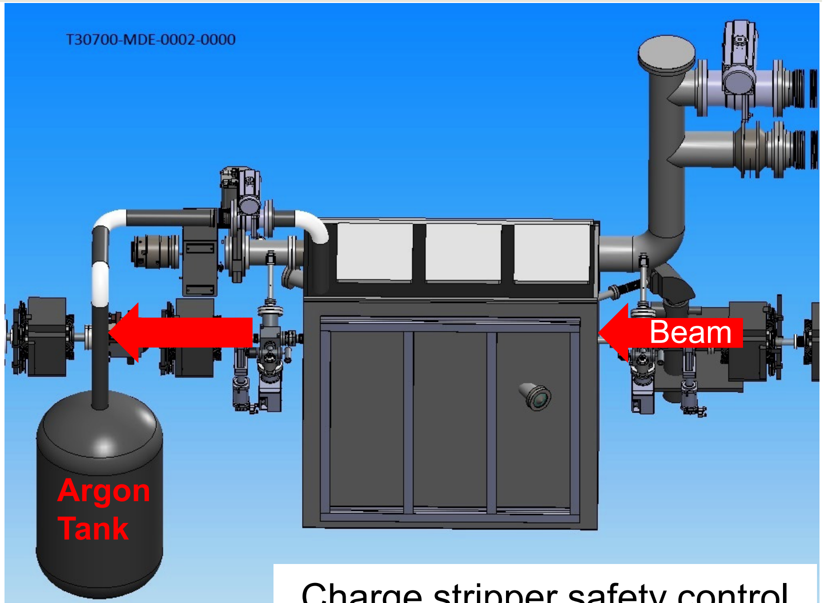
- Warm Compressor
  - Based on improved JLab 12 GeV Project design
  - Contract Award; delivery expected spring 2016
- Cryogenic transfer lines
  - Tunnel linear segment lines prototyped; production contract awarded
  - JLab WFO continues on vertical line manufacturing



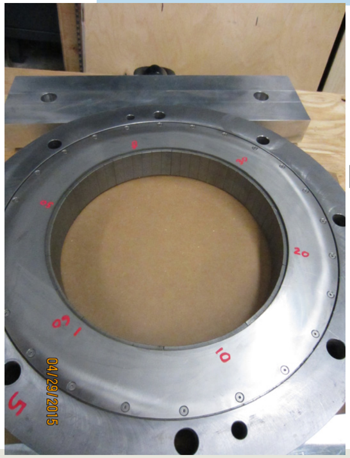
Charge Stripper Under Construction
Thoroughly Reviewed Liquid Lithium Safety Precautions

- Double-isolation with primary chamber contained by a secondary vessel continuously filled with inert argon gas
- Baseline liquid lithium stripper fabrication on track

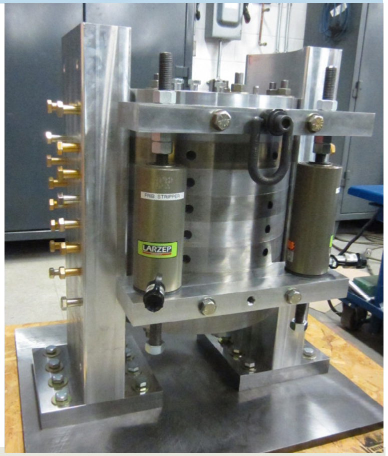




Charge stripper safety control

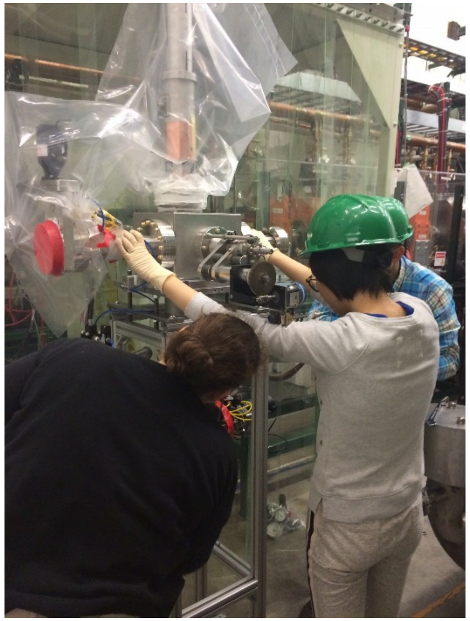


Assembly of lithium pump with permanent magnet rings



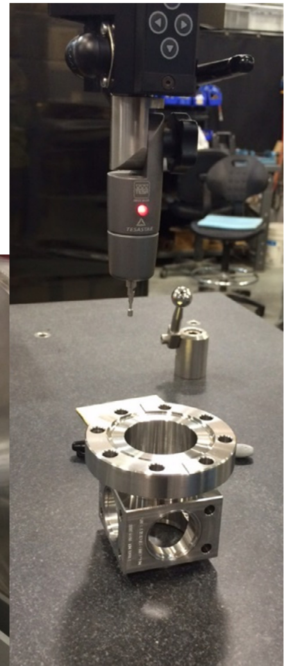
Diagnostic Systems
Moving from Design to Prototyping and Production

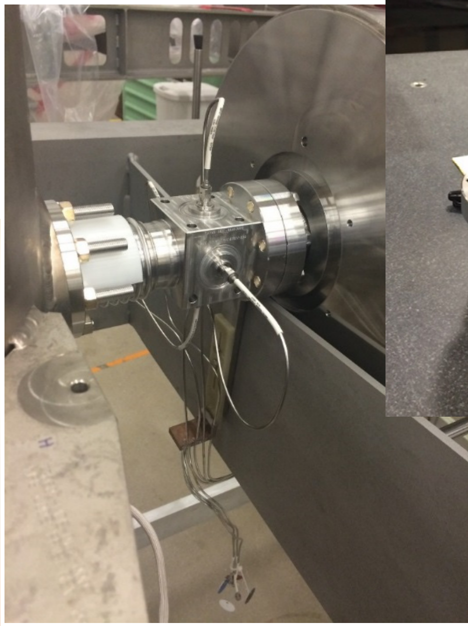
Installing prototype Bunch Shape Monitor on ReA



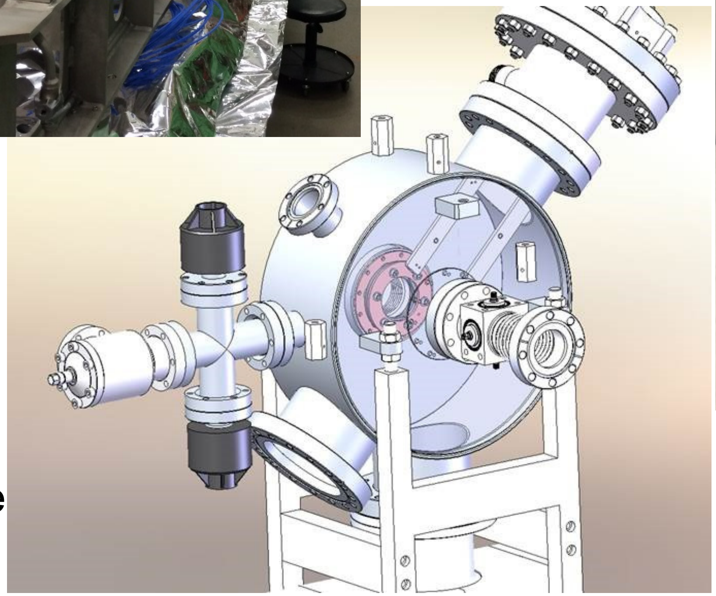
14-sensor wire position monitor installed on ReA6

BPM Production Assembly and Qualification at Supplier





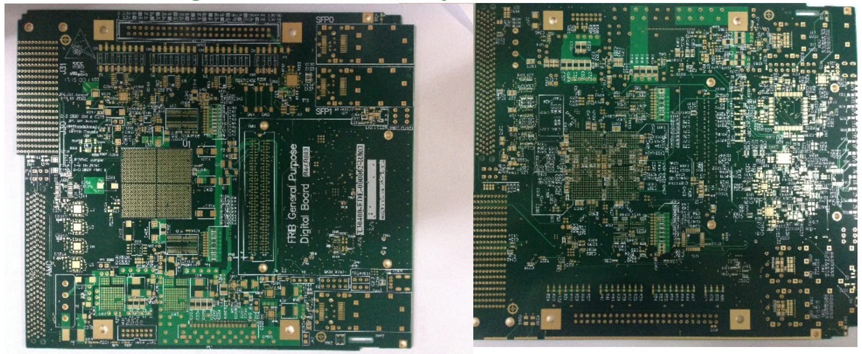
Cold BPM first article and cold cables installed on ReA cold mass



Design of integrated diagnostics box containing beam position, beam profile and halo monitor ring.

High-Level, Global Controls TBD
Closely Integrated on ASD, ESD, and NSCL Demands

- Personnel Protection System monitors selected; system to be installed and commissioned upon civil Ready-for-Equipment
- High level applications using ReA as a test bed; elog / etraveler / database supporting FRIB construction
- Global timing, machine protection closely interfacing with other systems



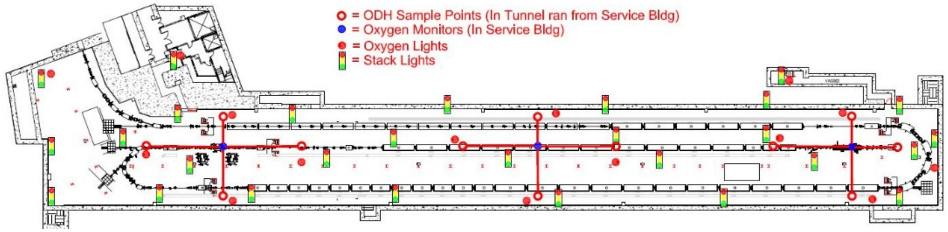
- Revised FRIB general-purpose digital boards status: Printed circuit boards produced, assembly underway at vendor

Radiation monitor contact awarded

Radiation detector contract awarded

Oxygen Deficiency Hazard monitor contract awarded

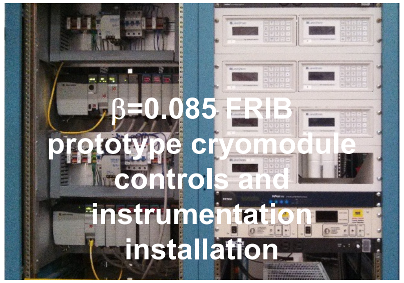
Linac Tunnel ODH Monitor Location

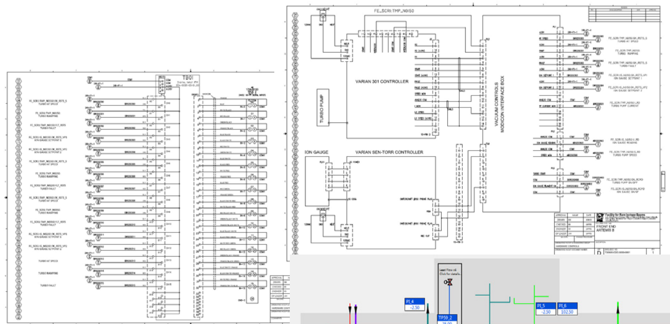


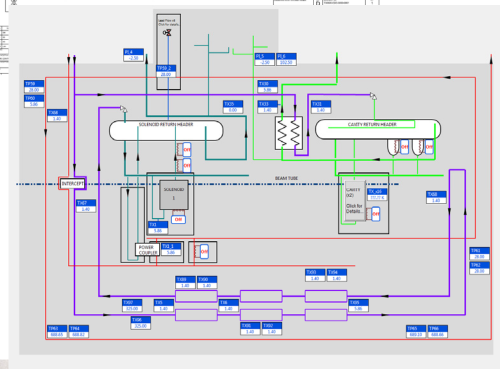
Low Level Controls Prototyping/Design

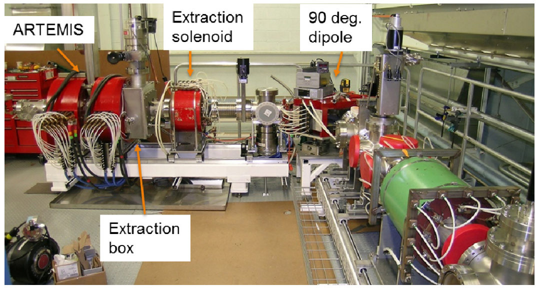
Using β=0.085 Prototype Cryomodule as a Test Bed

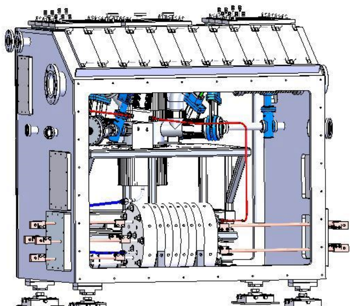
- ReA6 β=0.085 prototype cryomodule and cryo distribution line validated FRIB LLC design/architecture
- Front End controls final design reviewed
  - Procurement, fabrication and assembly to support early Front End installation
- Artemis room temperature ion source test stand controls installation underway
- Lithium stripper test stand controls design complete, procurements in process







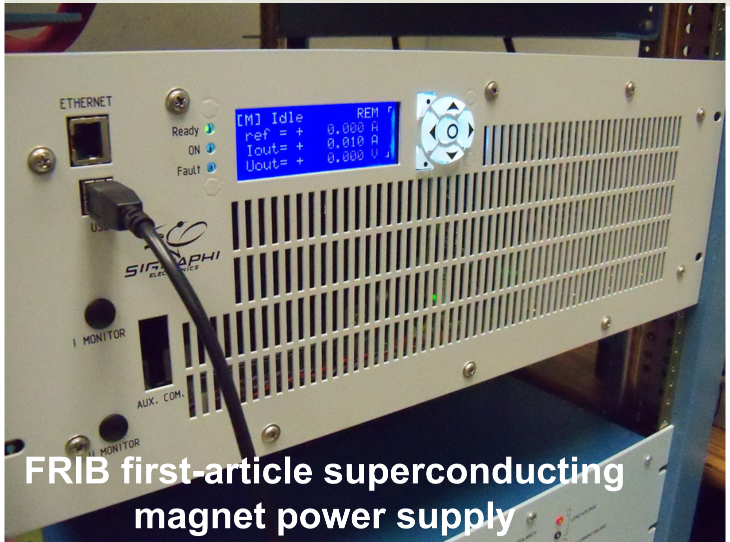




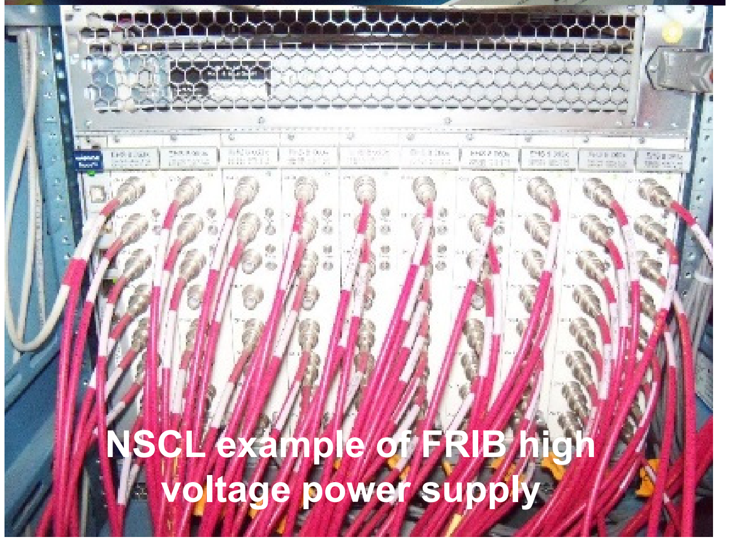
Lithium Stripper Test Stand

Power Supply: PS Final Design is Complete and all Major Procurements in Process

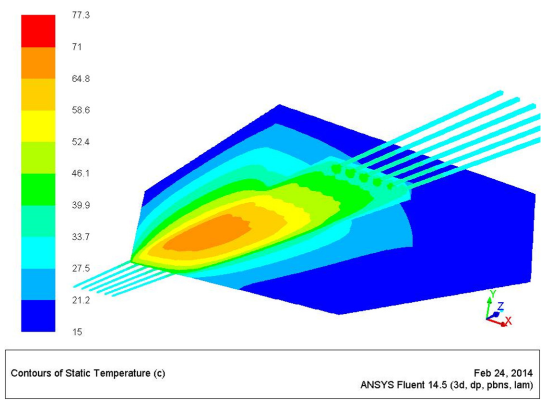
- SC magnet power supply (PS) contract awarded
- High voltage PS contract awarded
- Room-temperature magnet PS final contract awarded
- DC cable heating final design review completed
- Machine Protection System (MPS) / Dipole Power Supply (PS) Circuit Interface in progress



FRIB first-article superconducting magnet power supply


NSCL example of FRIB high voltage power supply

Example of commercial off the shelf digital DCCT for bending dipole power supply as part of Machine Protection System



Mutual heating simulation results for DC power supply cables

- Outlook

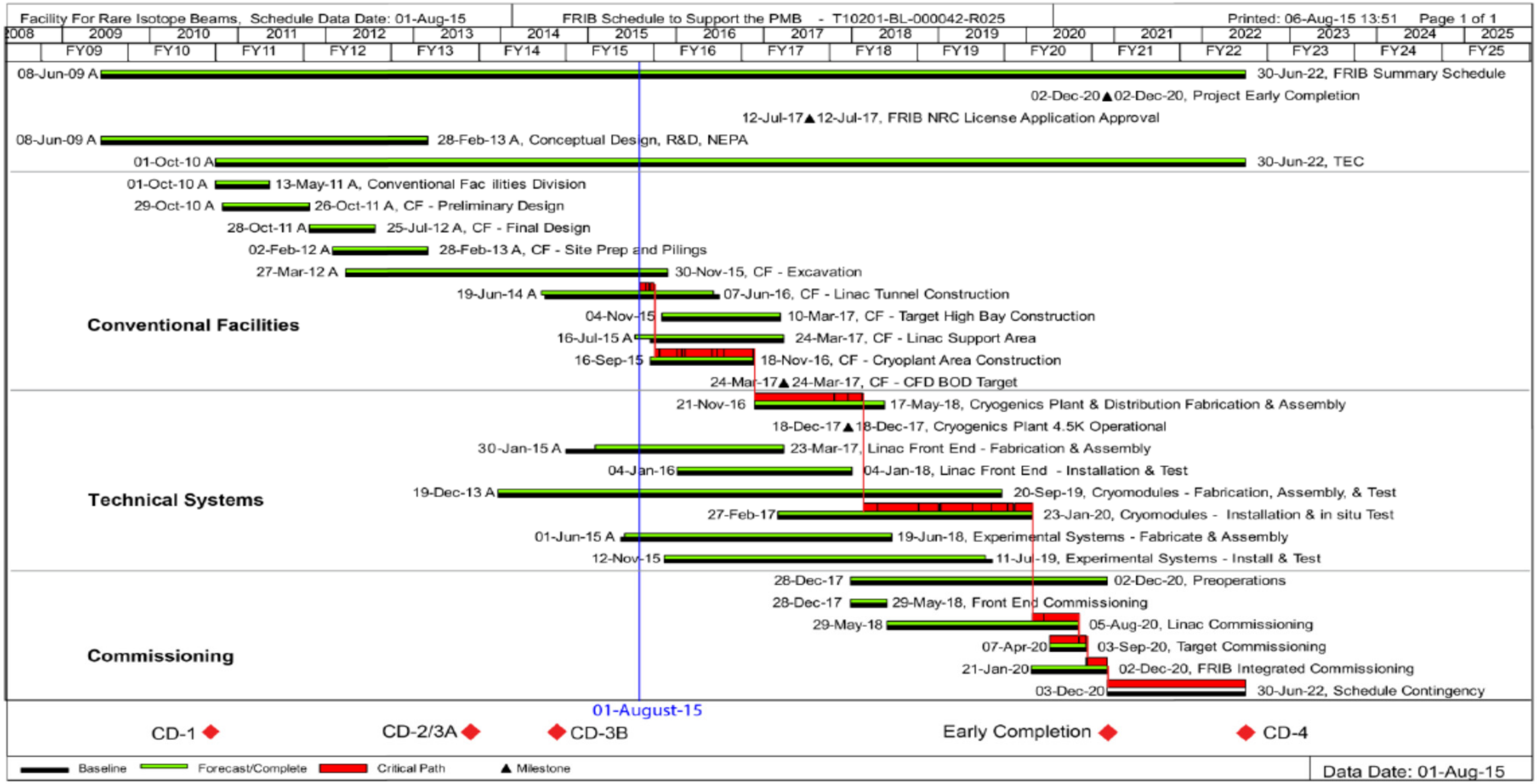
FRIB Integrated Master Schedule

Critical Path Shown in Red

Facility for Rare Isotope Beams
FRIB IMS Baseline Summary

FRIB -T10201-BL-000042-R0254
Issued 14 August 2015

FRIB Baseline Schedule Summary



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824 • Ph: (517) 355-9672
www.frib.msu.edu

Collaboration with Major Institutes

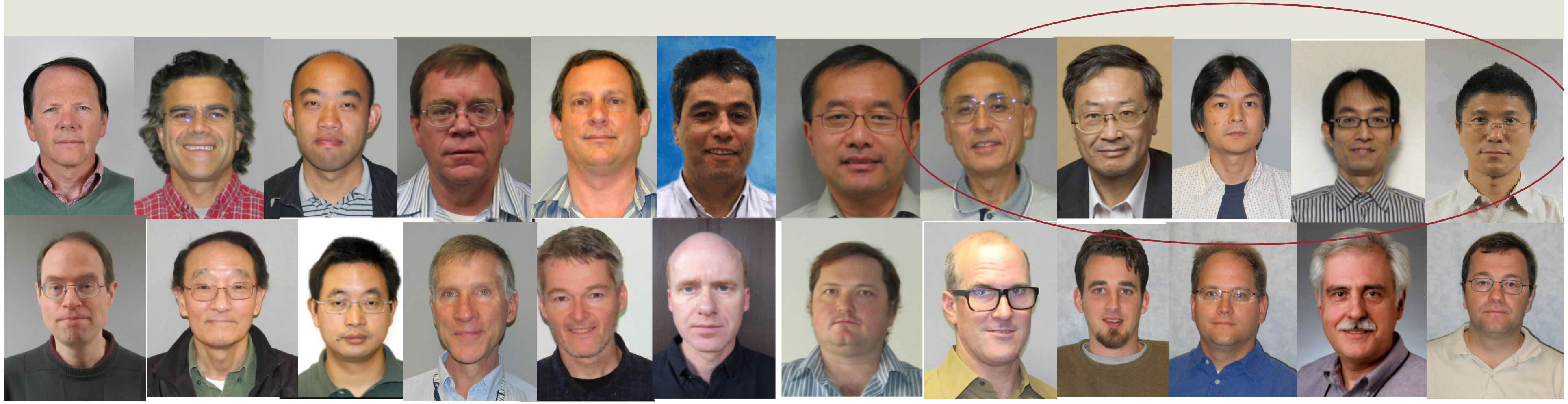
- ANL
  - Liquid lithium stripper
  - Beam dynamics verification; β=0.29 HWR design; SRF tuner validation
- BNL
  - Plasma window & charge stripper, physics modeling, database
- FNAL
  - Diagnostics, SRF processing
- JLab
  - Cryoplant; cryodistribution design & prototyping
  - Cavity hydrogen degassing; e-traveler **
  - HWR processing & certification*
  - QWR and HWR cryomodule design
- LANL
  - Proton ion source
- LBNL
  - ECR coldmass design; beam dynamics**
- ORNL
  - Diagnostics, controls
- SLAC**
  - Cryogenics**, SRF multipacting**, physics modeling
- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, physics modeling **
  - SRF, QWR etching
- INFN
  - SRF technology
- KEK
  - SRF technology, SC solenoid prototyping
- IMP
  - Magnets, SC solenoid measurement
- Budker Institute, INR Institute
  - Diagnostics
- Tsinghua Univ.
  - RFQ
- ESS
  - AP*
- DTRA
  - RFQ power supply**

* Under discussion or in preparation

** Completed

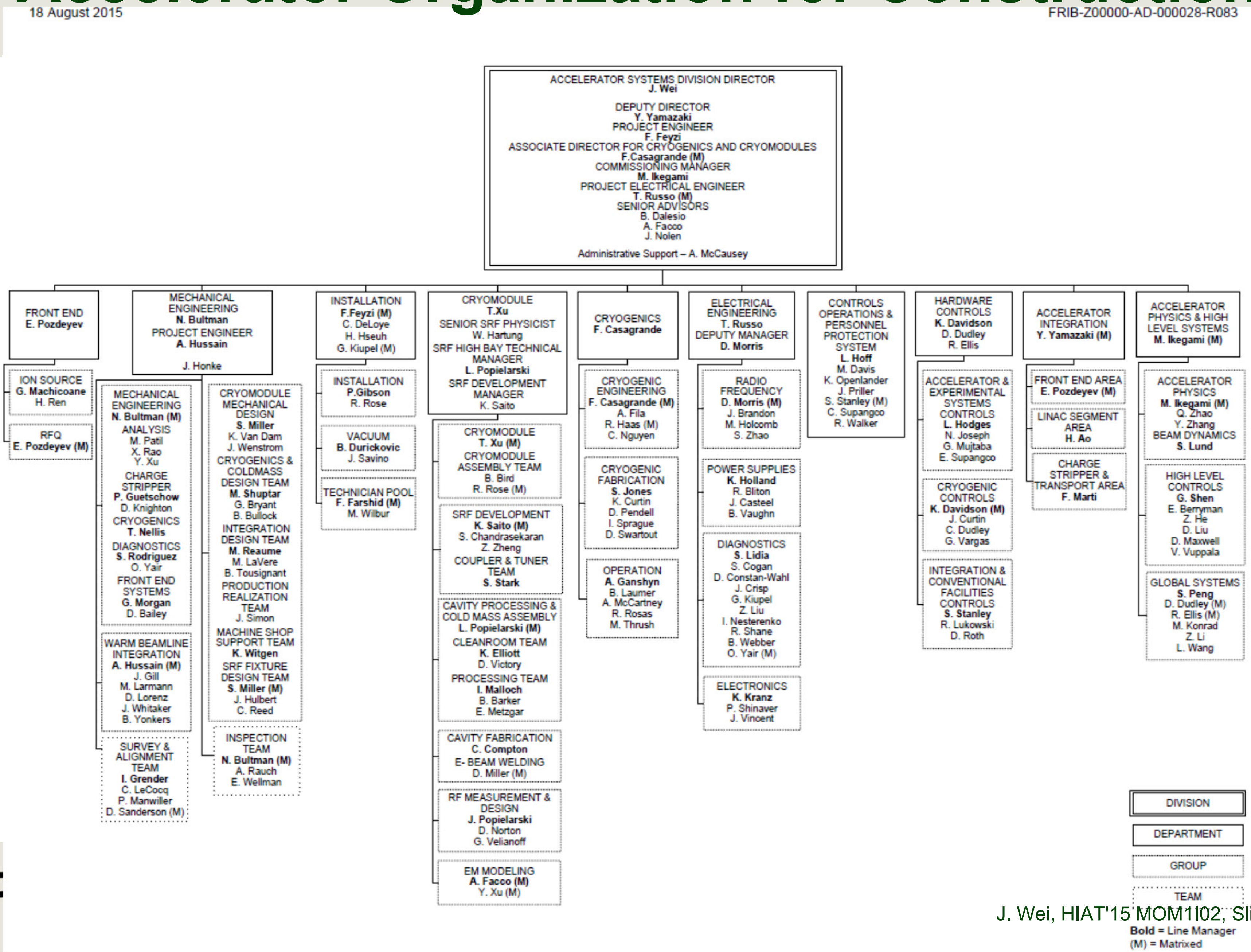
Red: Active/actively planned WFO contract

Attracted World Experts in Key Areas



- Attracted seasoned leaders in accelerator physics and engineering
  - H. Ao (J-PARC), N. Bultman (LANL), F. Casagrande (ORNL), L. Dalesio (BNL), A. Facco (INFN), F. Feyzi (Wisconsin), A. Ganshyn (Cornell), P. Gibson (ORNL), W. Hartung (Cornell), L. Hoff (BNL), H.-C. Hseuh (BNL), A. Hussain (BNL), M. Ikegami (J-PARC), R.E. Laxdal (TRIUMF), S. Lidia (LBNL), S. Lund (LLNL), G. Machicoane, J. Nolen (ANL), S. Peng (SLAC), E. Pozdeyev (BNL), T. Russo (BNL), K. Saito (KEK), G. Shen (BNL), H. Tatsumoto (J-PARC), J. Wei (BNL/THU), T. Xu (ORNL), Y. Yamazaki (KEK)
- Many colleagues joined FRIB from Japan!

Accelerator Organization for Construction



Summary

- FRIB Project is one year into full technical construction
  - Overall accelerator systems scope is 35% complete
  - Design is about 80% complete
  - Major procurement is 65% spent or committed
- Accelerator design meets FRIB performance requirements
  - Accelerator lattice footprint frozen since 2011
  - All major technology developments are completed
  - Optimized for availability, maintainability, reliability, tunability, upgradability
- An excellent team is in place to lead accelerator systems delivery
- FRIB is looking for dedicated fellows & seasoned colleagues to join the project, and also welcomes collaboration in all forms
- Thank you!

Thank You!